THE COASTAL IMPACT OF GROUND WATER DISCHARGE: AN ASSESSMENT OF ANTHROPOGENIC NITROGEN LOADING IN TOWN COVE, ORLEANS, MASSACHUSETTS

Final Report
(W.H.O.I. Proposal No. 2778)

Prepared for the Board of Selectmen
Town of Orleans, Massachusetts
November 14, 1983

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WOODS HOLE OCEANOGRAPHIC INSTITUTION
WOODS HOLE
MASSACHUSETTS

PREFACE

The shores of Town Cove have been settled for three centuries. As for most of Cape Cod, small, sparsely populated farming and fishing villages of the eighteenth century have given way to a substantial population of permanent residents today, with influxes of summer vacation residents and visitors that can increase the population several fold. Increasing numbers of our senior citizens retire to life-long vacation homes here or build new ones. Most people are attracted to the area because of its natural resources---the clean seaside environment, low wooded hills and the sheltered embayments, such as Town Cove, with clean shellfish, safe recreation and peaceful vistas.

Along with growth have come many of the problems of increased population pressure, such as disposal of wastes. Although this problem has several aspects, the one we are addressing has to do with sewage, or more specifically, with the nitrogen compounds associated with sewage that enter the groundwater and find their way to lakes, ponds, swamps and to the shores of Town Cove. This report contains our findings and assessment of the impact and potential impact of nitrogen from human sources on the Town Cove ecosystem, as well as advice to the Town on the potential impact of diverting sewage nitrogen destined for Town Cove to a nearby saltmarsh.

The decision on whether or not to spend substantial amounts of money to install sewers or a septage treatment plant depends on many kinds of technical, regulatory and economic information and projections into the future. In the end, it also depends significantly on individual perceptions of how things should be done and what is valuable. Our study is intended to fill an existing gap by providing expert technical information on how Town

Cove works and what nitrogen has to do with it; we cannot provide the other information and are not able to make the Town's decision on whether to install sewers.

The Woods Hole Oceanographic Institution is a private, non-profit institution dedicated to research in coastal and ocean marine sciences. For this project, funded mostly by the Town of Orleans, we assembled a team consisting of Institution staff with interest and expertise in the needed disciplines. The individual chapters making up this report represent the contribution by the author(s) in his or her area of interest, to our overall effort. Funds from the WHOI Sea Grant Program were used to initiate aspects of our research and paid half of Dr. Gaines' salary on this project. Also, Dr. Giblin's salary for this project came from the Andrew W. Mellon Foundation in the form of a Post Doctoral Fellowship awarded by the WHOI Coastal Research Center.

John M. Teal, Chairman
Department of Biology

EXECUTIVE SUMMARY FOR THE SELECTMEN

In this report we present scientific research on the nitrogen budget of Town Cove to help assess the role of human activities including the operation of on-site septic systems and possible future modification of existing nitrogen pathways. For many years, sewage-derived nitrogen has entered the ground water on Cape Cod, including in Orleans, causing elevated levels of nitrate in the ground water. Within the Orleans town center, nitrate levels in groundwater average about 3 to 4 ppm above other areas around Town Cove. With one possible exception, well water analyses in the Town center meet EPA nitrate standards for drinking water. Since the Town center area (and 95% of Orleans) is served by a municipal water system, however, drinking water considerations may be a separate issue. Our research in Town Cove focuses on the sources and fate of nitrogen, including its use by plants and in other biological activities.

1) A large number of chemical, biological and physical measurements have been made over the course of a year in Town Cove, which will stand as a baseline for future studies and impact assessments. These data indicate that Town Cove is a highly productive estuarine system, sharing many characteristics with other small coastal ponds in this area.

2) On the basis of a variety of biological and chemical indices, it is evident that the rate of algal productivity in Town Cove is not restricted by lack of nitrogen. It is still possible that future increased nitrogen loading could increase algal build-up in Town Cove.

3) Like similar coastal ponds on Cape Cod, the deepest water and sediment in Town Cove are devoid of oxygen for a portion of the year. Though this condition can occur naturally, it has also been caused or intensified by algal build-up from human activities. There is no evidence of fish or shellfish kills associated with this feature, although marine worms that occupy the deepest portions of the Cove are absent during periods of oxygen deficiency.

4) Quantities of nitrogen in dissolved and particulate form in the water column, buried in sediments, recycled by biological activity and passed in and out with the tides are very large compared with net additions or losses of nitrogen in Town Cove, such as from groundwater input or net tidal flux.

5) Several considerations, including the tidal asymmetry and the geometry of the Town Cove estuary, flow within the inner reaches of the Cove, as well as direct estimates, indicate this water body acts as a trap for particulate material. As a result, we believe substantial amounts of nitrogen, relative to groundwater inputs, are imported to the Cove by tidal flux.

6) Our best estimates suggest the Town center area could be contributing a significant fraction, perhaps 25-45%, of the net groundwater nitrogen input into Town Cove and possibly 10-20% of total nitrogen loading. This result is supported by an analysis of another group using different methods.

7) Certain elements of the nitrogen budget of Town Cove may be subject to modification by the Town or residents of Orleans. Activities involved could have a range of impacts on nitrogen loading and involve a wide range of effort, such as diverting surface runoff, minimizing application of lawn fertilizer, or modified septage pumping and disposal practices, each of which may account for as much as 5% of the net nitrogen influx. As implied above, diversion of all sewage-derived nitrogen from Town Cove could reduce nitrogen loading to Town Cove by about 10-20%.

8) The impact of freshwater and nitrogen from a possible septage/sewage plant on Namskaket Marsh has been assessed on the basis of scientific literature and our experience with nitrogen loading of marshes and wetlands elsewhere. Freshwater discharge into Hurley's Bog could cause noticable changes in the vegetation there, but would probably not have a strong effect on Namskaket Marsh. On the basis of available data, nitrogen loading from a septage or septage/sewage plant may exceed the assimilative capacity of Hurley's Bog, but we believe it is well within the assimilative capacity of Namskaket Marsh.

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INTRODUCTION

The overall objectives of this work are:

1) To characterize the groundwater composition in the Town of Orleans with special regard to its nitrate content.
2) To assess the relative significance of sewage-derived nitrogen in the nutrient budget of Town Cove (Fig. 1).
3) To advise the Town on the possible impact of a proposed sewage and septage treatment plant on the adjacent wetland, Namskaket Marsh.

The first objective is related to the second because in order to assess the impact of sewage-derived nitrogen on the Cove it is necessary to know the concentration of nitrate in groundwater entering the Cove. The third objective is germane to the Town's interest because both Town Cove and Namskaket Marsh are valued natural resources and, presumably, the Town does not wish to protect one to the detriment of the other.

Our basic approach is to prepare a nitrogen budget for Town Cove, including the major sources, sinks and pathways of nitrogen (Fig. 2). The contribution of our study to the Town's decision whether or not sewerage is required, will be to estimate the relative magnitude of sewage-derived nitrogen compared with other sources, and to assess the capacity of natural processes (physical, chemical and biological) in accommodating present and potential increased rates of nitrogen loading. In addition we will attempt to identify possible manifestations of stress to the system from existing or increased loading.

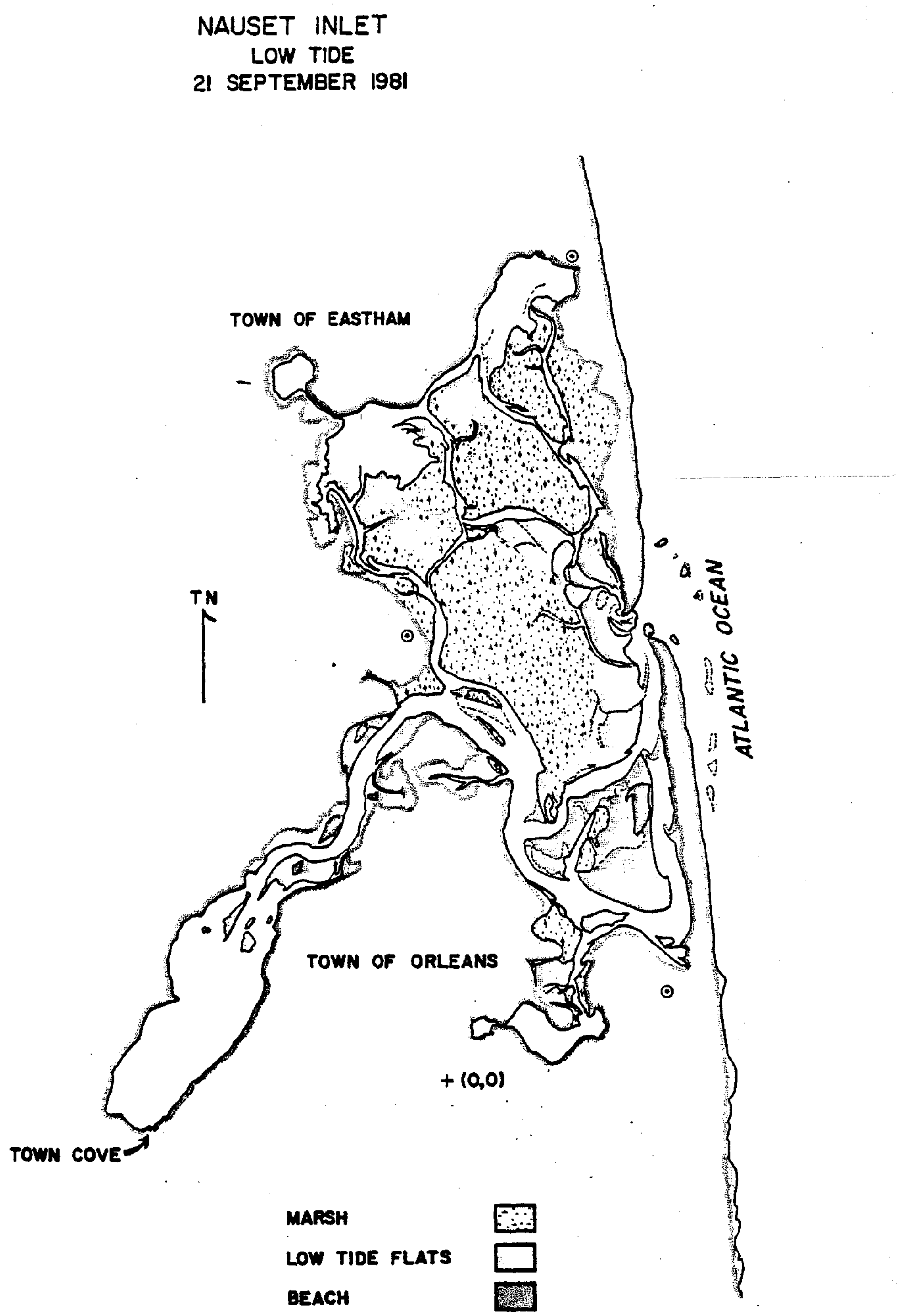

Figure 1. Town Cove and the Nauset Inlet bay complex Cape Cod, Massachusetts.

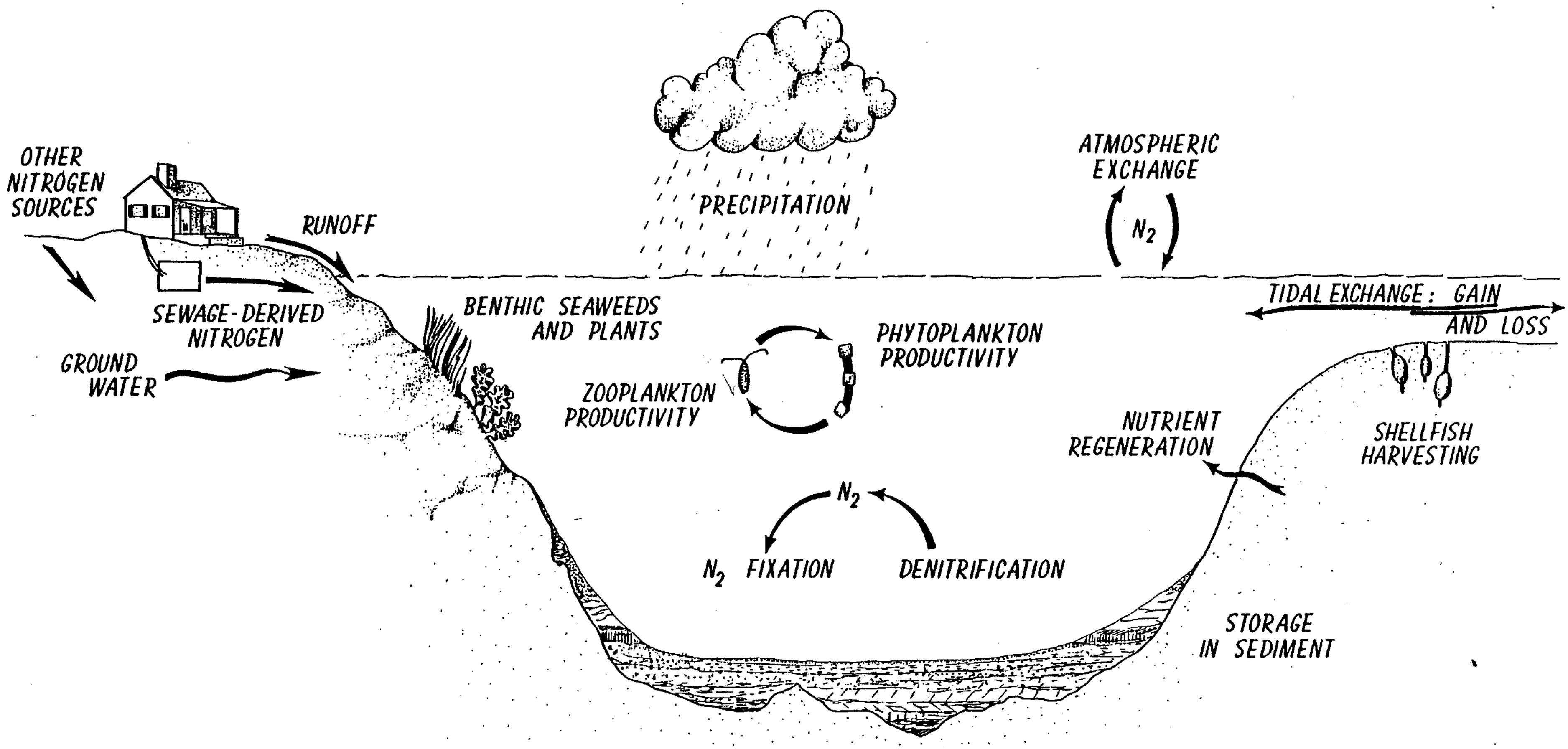

Figure 2. A schematic nitrogen budget for an estuary.

PART ONE - GROUNDWATER

Regional Context and Perspective

Arthur G. Gaines, Jr., WHOI Sea Grant Program

The issue of quality and management of groundwater on Cape Cod has been examined by the Cape Cod Planning and Economic Development Commission and their consultants under an EPA 208 planning program, resulting in the production of a report in 1978 (CCPEDC, 1978) and an ongoing program of groundwater management activities at the planning district level. Over the past five years studies conducted on Cape Cod by the U.S. Geological Survey have addressed groundwater quality (Frimpter and Gay 1979), computer modeling of regional groundwater flow (Guswa and LeBlanc 1981), the Cape Cod aquifer (Ryan, 1980) and more localized issues such as a case study of groundwater contamination by the wastewater treatment facility at Otis Air Force Base in Falmouth (LeBlanc, 1982). These and other works provide a background against which groundwater issues in Orleans, including our assessment of nitrate content, gain perspective.

A. Groundwater flow

Although the Cape Cod aquifer has recently been designated by EPA as a "sole source aquifer", the flow of groundwater here has actually been represented as five separate principal groundwater systems (Guswa and LeBlanc, 1981). The Orleans wellfield falls within the "ECAPE" system, shared by neighboring towns to the south and west; in addition, Town Cove receives discharge from the "ESTHM" system, centered in Eastham (Fig. 3). Although regional patterns of groundwater flow have been mapped (CCPEDC, 1978, map 5.2; D.E.Q.E. Groundwater Atlas, unpublished), the details of the flow or the exact position

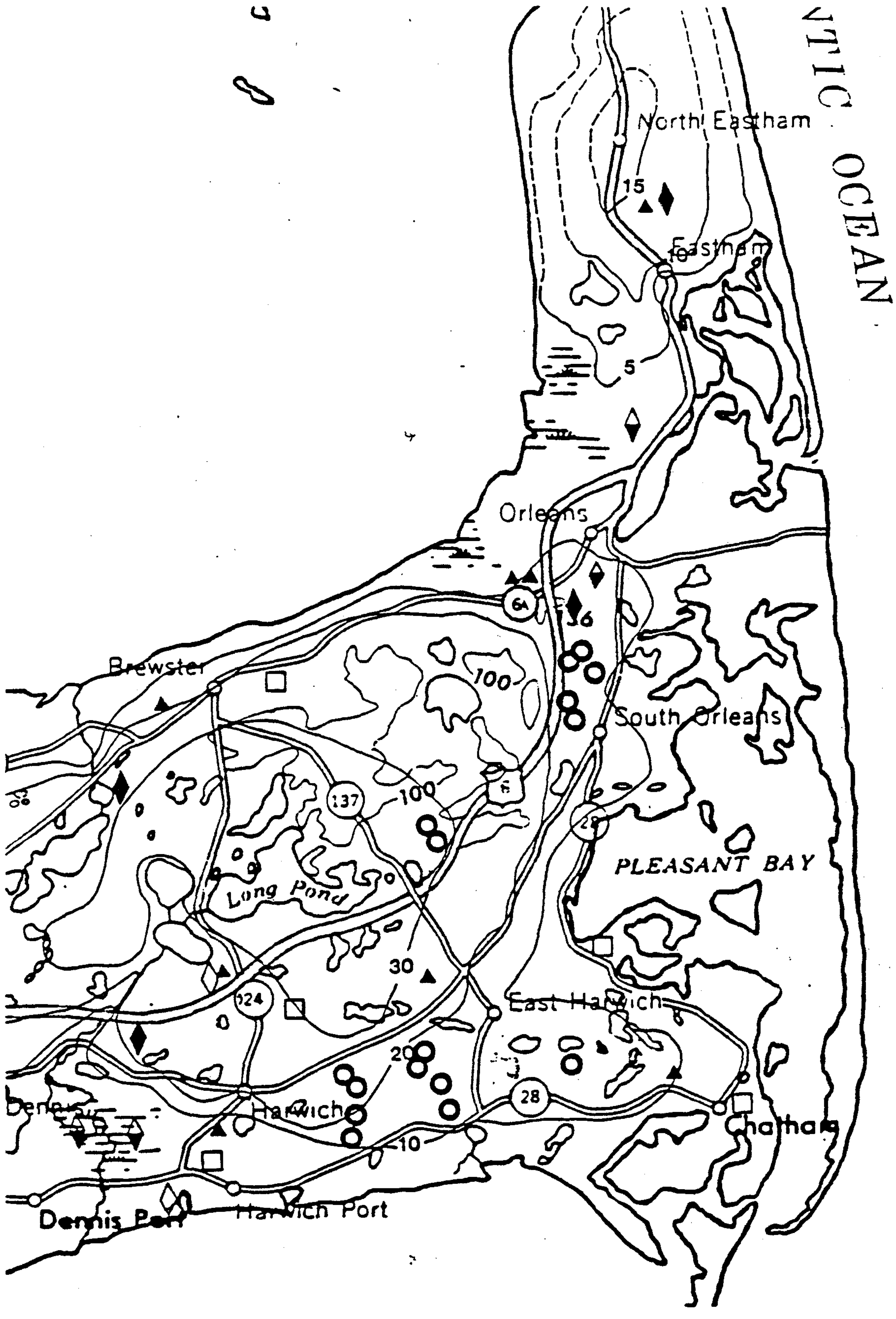

Figure 3. Contour map of the water table in the vicinity of the Town of Orleans, Massachusetts. Elevation in feet above sea level. ▲ = sal storage area; ◆ = active landfill; ◇ = inactive landfill or septage disposal area; ○ = public supply well; □ = golf course. (modified from Ryan, 1980).

of the recharge divide at the local level, such as within the Town of Orleans or the Town Center, are known only approximately (LeBlanc, personal communication). In terms of the present study this is significant for two reasons: a) it puts limits on how precisely one can specify the proportion of groundwater and groundwater-contaminants from the Town Center or other areas surrounding Town Cove that move toward the Cove, as opposed to toward Cape Cod Bay or elsewhere; and, b) it adds to the difficulty of locating the effluent plume from the present Orleans landfill and septage disposal area.

Groundwater in an island or peninsular aquifer, such as Cape Cod, is generally portrayed to assume the configuration of a lens of freshwater "floating" on saline groundwater which permeates the sediments below and seaward (Fig. 4). The fresh and saline water is typically separated by a finite interface, or mixing zone. On the lower Cape this freshwater lens probably extends to depths of at least 150 to 200 feet below sea level (cf. Fig. 19 in Guswa and LeBlanc 1981). The streamlines of flow characteristic of this kind of aquifer are such that rainfall or contaminants entering near the recharge divide can be

expected to follow a path bringing them to greatest depth in the aquifer, while recharge near the coast or other discharge areas follows a shallower trajectory. In either case, eventual discharge is expected in the nearshore coastal area. In the case of Orleans, with its deep embayment systems, the details of groundwater flow and discharge can be expected to be considerably less straightforward than this simple model. Furthermore, the simple isotropic model of groundwater flow often breaks down on Cape Cod at the local level (Oldale, personnel communication), as will be discussed later. Nevertheless, these groundwater generalizations have two bearings on the present study.

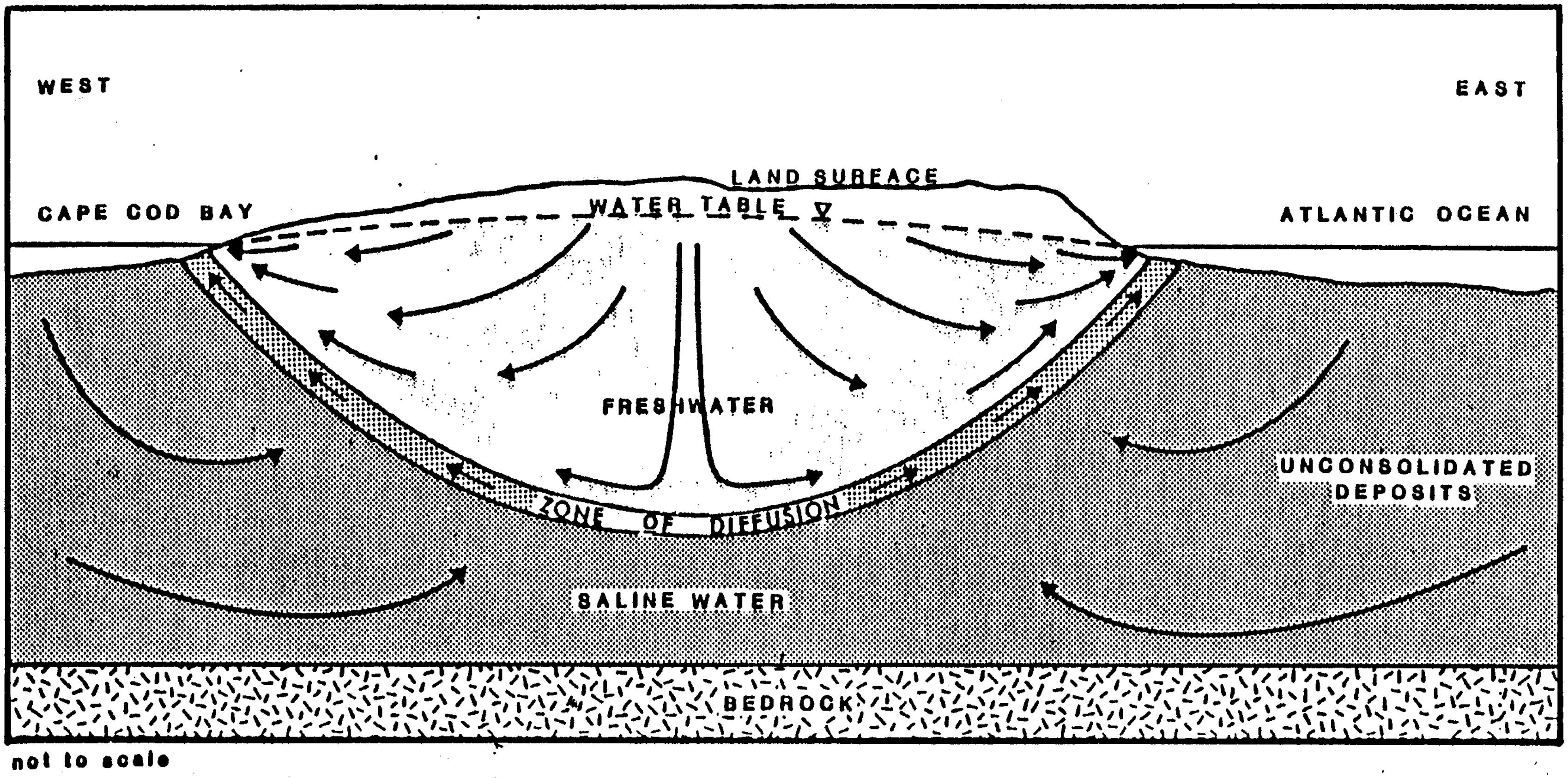

Figure 4. Schematic section of the Cape Cod aquifer (from Ryan, 1980).

First, the present Orleans landfill and septage disposal area appear to lie near the groundwater divide, and the plume would be expected to descend in the aquifer, initially, on its course to the sea. This suggests that away from the immediate vicinity of the landfill only deep or coastal wells would be expected to intercept the plume: in fact, to date we have not observed any groundwater samples containing nitrate at the level to be anticipated in a landfill or septage plume. The highest level of nitrate measured in the vicinity of the landfill in our study was 6.7 ppm (NO_3^--N), compared with 18.4 ppm observed in the Dennis landfill plume (EMI, 1976), up to 24 ppm in the Otis sewage plume (LeBlanc, 1982), or more than 11 ppm previously recorded in a well (since destroyed) in the Orleans landfill (Schofield Brothers 1972). One reason we may not have detected this plume is that the wells available for sampling are shallow wells and the plume may pass beneath them.

Secondly, our sampling pattern and density, again largely imposed by the availability of wells may not have been sufficiently dense to intersect the plume, which could be quite narrow. A study of the Babylon and Islip landfills on Long Island, NY, for example, by Kimmel and Braids (1974; cited in CCPEDC, 1978) showed the plumes at 10,600 feet and 5,000 feet distance, respectively, were not appreciably larger than the dimensions of their source. The Otis plume on Cape Cod, while considerably wider (presumably resulting from the very large volumes of effluent involved) also does not spread appreciably with distance from the source (LeBlanc 1982). The ultimate fate of dissolved materials from the Orleans landfill is a topic of considerable concern to the Town, and we will elaborate on this topic below. At this point, however, it should be mentioned that there is a difference of opinion amomg experts as to the direction the landfill plume probably takes; according to Schofield Brothers (1972), based on their interpretation of groundwater contours, the plume follows an azimuth of about 75° (T) toward Crystal Lake. On the other hand, GZA (1982) concludes the plume moves approximately 35° (T) toward Town Cove.

The second significance to our study of the generalized view of groundwater flow on Cape Cod bears on the coastal location of the proposed septage or septage/wastewater treatment plant. It is reasonable to assume from Fig. 4 that the leachate at a coastal site would follow a shallow path and discharge in the wetlands nearby; LEA has indicated they, also, expect this to happen at Namskaket Marsh (Weisman, personal communication).

B. Nitrogen Content of Groundwater

The nitrate content of groundwater is used as an index of water quality because, a) at high levels it is known to be toxic to man and, b) it is a constituent or product of domestic sewage that is not completely trapped in septic systems and can therefore be used as a tracer of septic leachate. EPA set an upper limit of 10 ppm (nitrate N) on groundwater used for drinking purposes. Our analyses of the Orleans Town wells, in the course of this study, in agreement with those of the county and state agencies (CCPEDC 1978; LEA, 1981a), indicates nitrate levels are very low in the Orleans municipal water. Our measured values for all five Town wells were less than 0.1 ppm, or less than 1% of the EPA standard. Among 94 public wells on Cape Cod the Orleans well water ranks among 16 with lowest nitrate (CCPEDC 1978, Table 3.6). Since more than 95% of the Town of Orleans is served by this public system (Kimball, 1983), the issue of nitrate contamination of drinking water need not be of general concern on an <u>areal</u> basis in Orleans.

In this study, our principal interest in groundwater composition is its potential impact at discharge sites, with specific attention to nitrogen loading in Town Cove, although we recognize the data could be used for other purposes. Fig. 5 gives the distribution of nitrate concentrations in 116 wells in Orleans and Eastham. These data are mainly from the Barnstable County Health Department and represent values for primarily shallow, domestic wells including all available values determined through the summer of 1983. Some of the analyses (indicated by circles in Fig. 5) are our own, and represent samples collected from observation wells, active and inactive domestic wells and institutional wells.

Nitrate concentrations in well water varied from 0.0 to 10.5 ppm with widespread but sporadic values greater than 3.0 occurring in Orleans and Eastham. Among the ten highest values shown on this figure, three occur within the general business district and limited business district of the Orleans Town center; one is located off Giddiah Hill Road in the vicinity of the landfill; and one is associated with the Nauset Middle School auxiliary well. The remaining five wells in this category occur in Eastham. Only one sample in Orleans Town center exceeded 10 ppm nitrate-nitrogen and this sample may have been contaminated in the collection process. Within a 1 kilometer radius of the intersection of Route 6A and Main Street in Orleans Town center, the nitrate concentration in wells ranged from 0.0 to 10.5 ppm, and averaged 2.9 ppm (17 samples; S.D.=2.7). Half of the wells analyzed in this area exceeded 2.2 ppm.

It is informative to put these results in a broader perspective. The Environmental Management Institute (1976) collated 501 groundwater analyses for water from private wells on Cape Cod, including 136 of their own supplemental

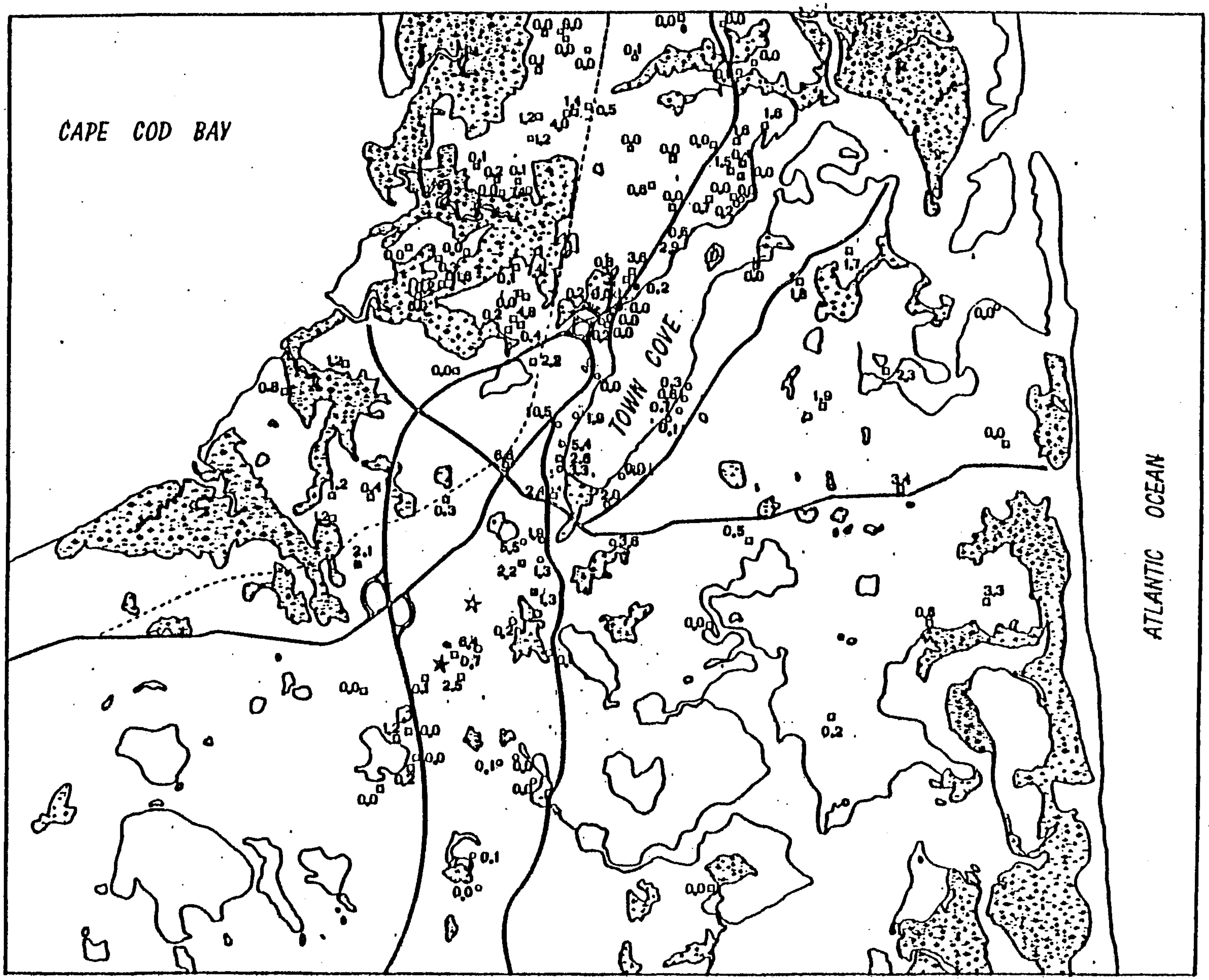

Figure 5. The distribution of nitrate concentration in groundwater in the Orleans Quadrangle, Massachusetts. Generally wells samples were shallow domestic wells. Circles indicate analyses by WHOI. Other data from Barnstable County Health Department and LEA, 1981. Units of parts per million (ppm). ★ = present landfill ☆ = former landfill

analyses, as part of a study conducted for the EPA 208 program (CCPEDC, 1978). A frequency distribution of these data (Table 1) indicates water from more that half the wells on Cape Cod contained less than 0.5 ppm nitrate, and 90% contained less than 3.9 ppm; 4% exceeded the EPA standard of 10 ppm. In the Orleans Quadrangle area, which includes parts of Orleans and Eastham surrounding Town Cove (Fig. 5), about half of the wells analyzed contained less than 0.4 ppm and 90% contain less than 3.4 ppm; 1.7% exceeded the EPA standard (Table 1). In terms of the areal distribution of nitrate in domestic and other shallow wells, the data from the Orleans Quadrangle are similar to Cape Cod in general in that comparatively high groundwater nitrate values are widespread though sporadic. Also, densely populated or business areas appear more characterized by absence of very low values than by the presence of exceptionally high ones. In Table 1, 23% of nitrate levels for Cape Cod as a whole lie between 1.0 ppm and 5.4 ppm; the comparable value for our Orleans Quadrangle data set is 30%, and within the Town center area, 65% of wells analyzed fall in this concentration range.

The Environmental Management Institute (1976) study also assessed the long-term ("steady state") effect of on-site septic systems on the nitrate content of groundwater on Cape Cod, using a computer model. In essence, the model considered the cumulative impact of successive additions of nitrate to groundwater along selected trajectories, taking into account that recharge acts to dilute the contaminant along the way, as well as considerations of groundwater flow. The distribution of septic systems was based on the observed or projected population distribution on Cape Cod. The results indicate fewer wells with less than 0.5 ppm would eventually be expected on Cape Cod (Table 1 column C)

Table 1. Frequency distributions for nitrate concentrations in well water. A) Cape Cod (data from EMI 1976). B) Orleans Quadrangle (values in parentheses are for the Town center area). C) EMI (1976) groundwater model steady state calculations for Cape Cod.

Nitrate Concentration Range (ppm N)	Percent of Analyses A) Cape Cod (501 samples)	B) Orleans Quadrangle[a] (116 samples)		EMI Model (512 points)
0.0–0.4	59.0	55.0	(18)	45.1
0.5–0.9	10.1	8.6		24.1
1.0–1.4	7.7	7.8	(12)	7.8
1.5–1.9	4.2	7.8	(12)	6.1
2.0–2.4	2.9	5.2	(24)	6.1
2.5–2.9	2.9	2.6	(6)	4.3
3.0–3.4	2.3	2.6	(6)	2.0
3.5–3.9	1.5	1.7		1.6
4.0–4.4	1.7	0.9		1.0
4.5–4.9	1.3	0.9		0.6
5.0–5.4	0.6	0.9	(6)	0.6
5.5–5.9	0.6	0.9	(6)	0.0
6.0–6.4	0.0	0.9		0.2
6.5–6.9	0.0	0.9	(6)	0.2
7.0–7.4	0.2	1.7		0.0
7.5–7.9	0.2	0.0		0.0
8.0–8.4	0.0	0.0		0.2
8.5–8.9	0.0	0.0		0.0
9.0–9.4	0.5	0.0		0.0
9.5–9.9	0.0	0.0		0.0
over 10	4.0	1.7	(6)	0.2

[a]Data from WHOI, Barnstable County Health Department and LEA (1981a).

than observed to date (Table 1, column A) but 90% of the calculated nitrate concentrations were still less than 2.9 ppm and only 0.2% (1 well located in the Otis waste treatment plume) exceeded the EPA nitrate standard.

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Freshwater Discharge and Nitrate Input into Town Cove

Arthur G. Gaines, Sea Grant Office
Anne E. Giblin, Department of Biology
and
Zofia Mlodzinska-Kijowski, Department of Chemistry

A principal objective of this study is to determine the relative magnitude of sewage-derived nitrogen in Town Cove, compared with other components of the nitrogen budget. The composition of groundwater, runoff and precipitation as well as estimates of their magnitudes are needed for these determinations.

A. Nitrogen content of groundwater

Over the course of the study, nitrogen determinations were made on samples collected from seeps and springs entering Town Cove ("NS" samples), on special observation wells (Beach Wells) established around the margin of the Cove ("BW" samples), and on active and disconnected, domestic residential wells (RW and RWd samples) located at or near the shoreline (Fig. 6). The results (Table 2) suggest groundwater composition shows a large variation in space, but rather small temporal variation at any given site. The nitrate concentration varied from 0.0 to 9.8 from site to site; but, for example, at NS 8 the range over 11 months was 4.4 to 5.5 ppm (n=5; avg.=5.1 ppm; S.D.=0.55ppm). On the basis of these data, groundwater entering the Cove can be divided into three provinces characterized by the spatial trend in nitrate level (Table 3). These estimates of nitrate concentration (column A) were adjusted by taking into account nearby well values, given in Fig. 5, to give the estimates listed in Column B of Table 3; regarded as the best estimates available for the concentration of nitrate in groundwater entering Town Cove.

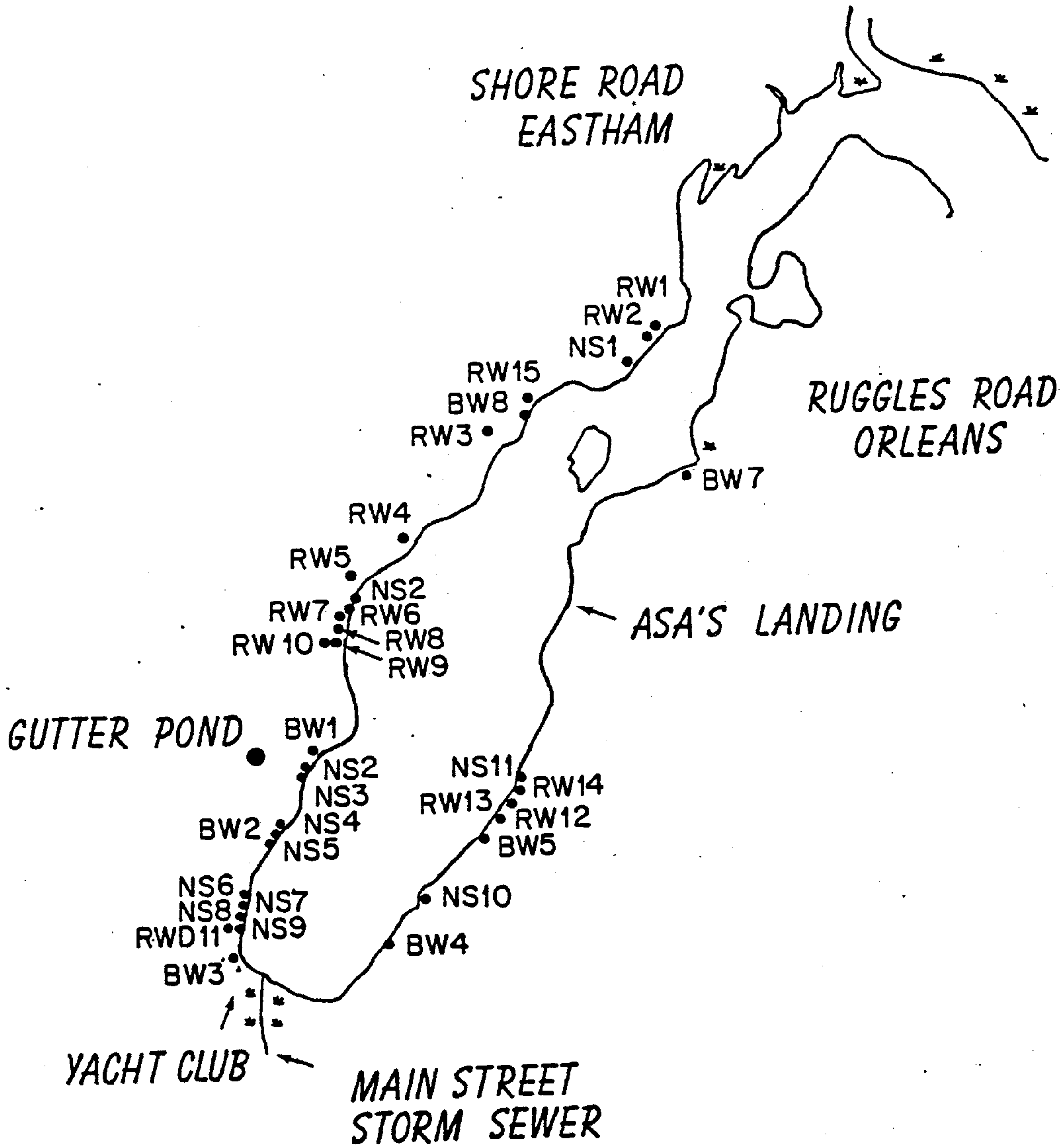

Figure 6. Locations of groundwater and surface run-off sampling locations, Town Cove, Orleans Quadrangle, Massachusetts. RW= residential well; RWd=discontinued residential well; BW=specially established observation wells; BWF= specially established temporary wells in the intertidal beach face near BW locations; NS= natural seep or spring.

Table 2. Nitrate concentration (ppm NO_3-N) in groundwater at shoreside stations around Town Cove from Shore Road, Eastham to Ruggles Road, Orleans, Mass. August 6, 1982 to July 19, 1983 (see also Fig. *).

Station –	Date									
	1982						1983			
	8/6	8/8	8/27	10/8	10/21	11/5	2/4	6/2	6/30	7/19	All[a]
Shore Road, Eastham											
RW 1							0.0	0.0			0.0
RW 2							0.2				0.2
NS 1			0.0								0.0
RW 15								0.6			0.6
BW 8							1.3				1.3
RW 3	2.9										2.9
RW 4	0.2										0.2
RW 5							0.0	0.0			0.0
NS 2	0.0		0.0					0.0			0.0
RW 6	0.0										0.0
RW 7	0.0										0.0
RW 8	0.0										0.0
RW 9	0.2										0.2
RW 10	0.2										0.2
BW 1					0.0						0.0
BWF 1					0.0						0.0
NS 2			0.6								0.6
NS 3			0.3				0.1				0.2
BW 2					1.9		9.8		0.3[b]		4.0
NS 4			2.1								2.1
NS 5			3.1								3.1
NS 6			0.7								0.7
NS 7			2.5				3.8	4.4			3.6
NS 8			4.4		4.8		5.5	5.8		5.2	5.1
NS 9					1.9		3.0	1.7		2.0	2.2
RWd 11				5.5							5.5
BW 3					3.4				1.8[b]		2.6
BWF 3					0.0						0.0
BW 4					0.0			0.0	0.0		0.0
BWF 4					0.0						0.0
NS 10			1.1					1.3			1.2
BW 5					0.1		0.1	0.1	0.0		0.1
BWF 5					0.9						0.9
RW 12	0.3							0.0			0.2
RW 13	0.6							0.0			0.3
RW 14	0.7							0.2			0.5
NS 11								0.6			0.6
BW 7					0.0		0.1	0.0			0.1
Ruggles Road, Orleans											

(RW=residential well; RWd=residential well, discontinued; NS=spring or seep; BW=beach well; BWF=beach face well)

[a]"All" column tabulates all values or their averages where more than one analysis exists.

[b]Newly established well on site adjacent to destroyed well.

Table 3. Town Cove groundwater discharge provinces (August 6, 1982 to July 19, 1983; n = number of analyses; x = average value). Orleans Quadrangle, Massachusett

Province	A[1] Nitrate Average (ppm)		B[2] Nitrate Average (ppm)		% of Total Discharge[3]	% Nitrogen Loading
	n	x	n	x		
Eastham Shoreline	14	0.4	26	1.0	29	21
Orleans Business District	14	2.1	22	2.9	21[4]	45
Tonset/Weeset Shoreline	10	0.4	13	0.9	50[4]	33

[1] Includes data from Table 2 only.
[2] Combines data from Table 2 with adjacent data from Fig. 5.
[3] % of total discharge is based on the relative shoreline length for each province.
[4] Includes artificial recharge

B. Freshwater discharge into Town Cove

A portion of the precipitation falling on land surrounding Town Cove runs off as surface water or evaporates, and the remainder enters the groundwater system as recharge. According to Strahler (1972), relatively large fractions of precipitation infiltrate into the sandy sediments of Cape Cod and, a compared to other areas large fraction is lost by evaporation or plant transpiration to the atmosphere. Thus, of the 47 inches of precipitation rain typical for a year in ? this area (National Weather Service, 1982, 1983), as little as 3 to 9 inches become surface runoff. Between 13 and 18 inches typically contribute directly to groundwater recharge (Horsley, CCPEDC, personal communication). Both runoff and recharge carry with them nitrogen from fertilizer, wild and domestic animal wastes, organic degradation materials, emission products of combustion and other sources. Beneath the ground, leachate from septic systems adds materials to the groundwater, such as nitrate, that are not effectively removed by microbial, sorption reactions or chemical reactions in and around the system.

1. Groundwater Discharge

Average monthly precipitation on the outer Cape shows considerable spread around 30 year averages (Fig. 7). The unusually wet 1982-1983 year illustrates this well, and the resulting recharge produced an abrupt rise in the water table (Fig. 8). It is evident that similar events have occurred over the past 7 years.

Simple models of groundwater movement on Cape Cod assume an unconfined aquifer in an isotropic medium. At the large scale these assumptions appear

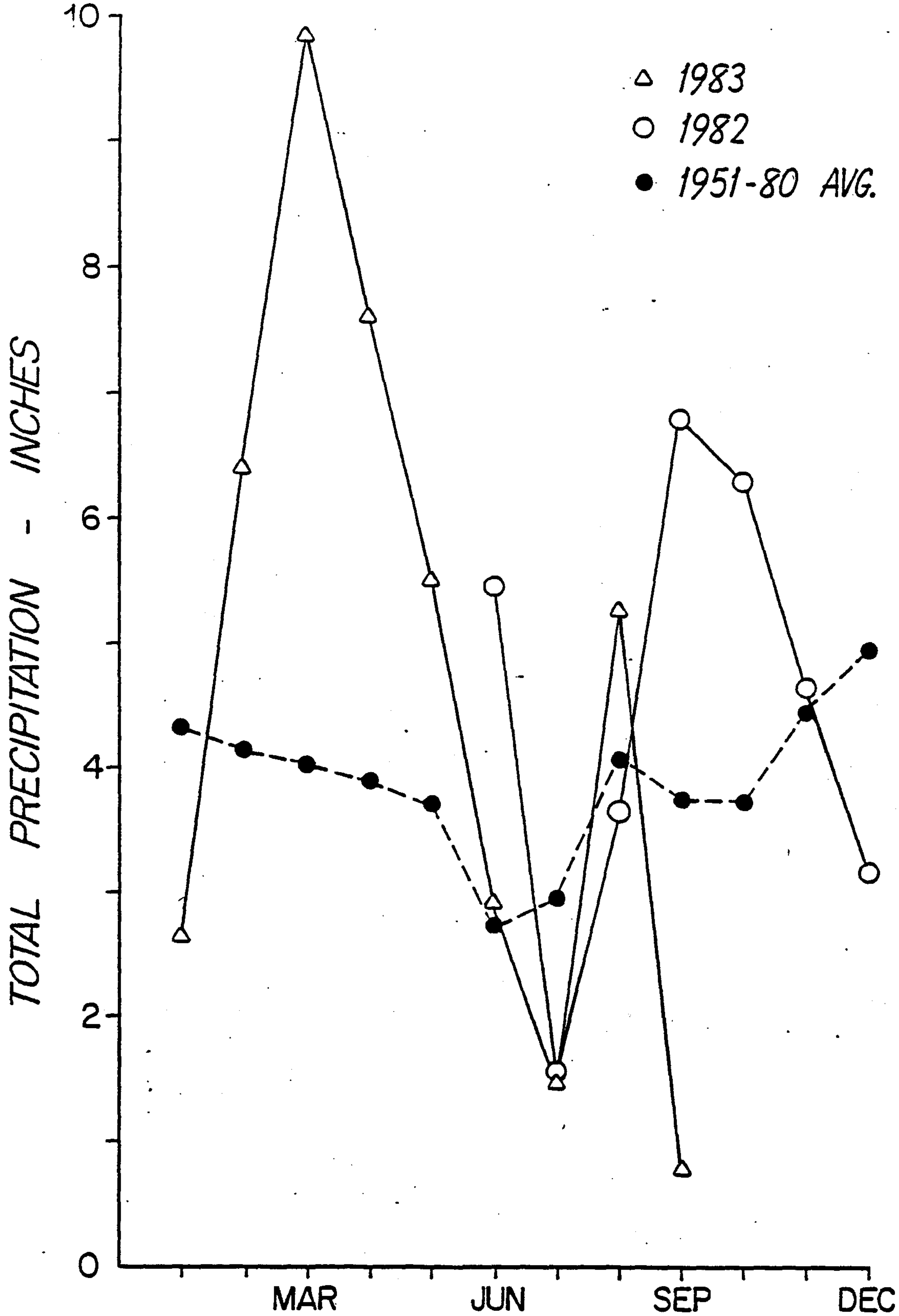

Figure 7. Average monthly precipitation data for 1982-1983 (open symbols) and average monthy values for 1951-1980 (solid circles for observations at WSMO Chatham Massachusetts.

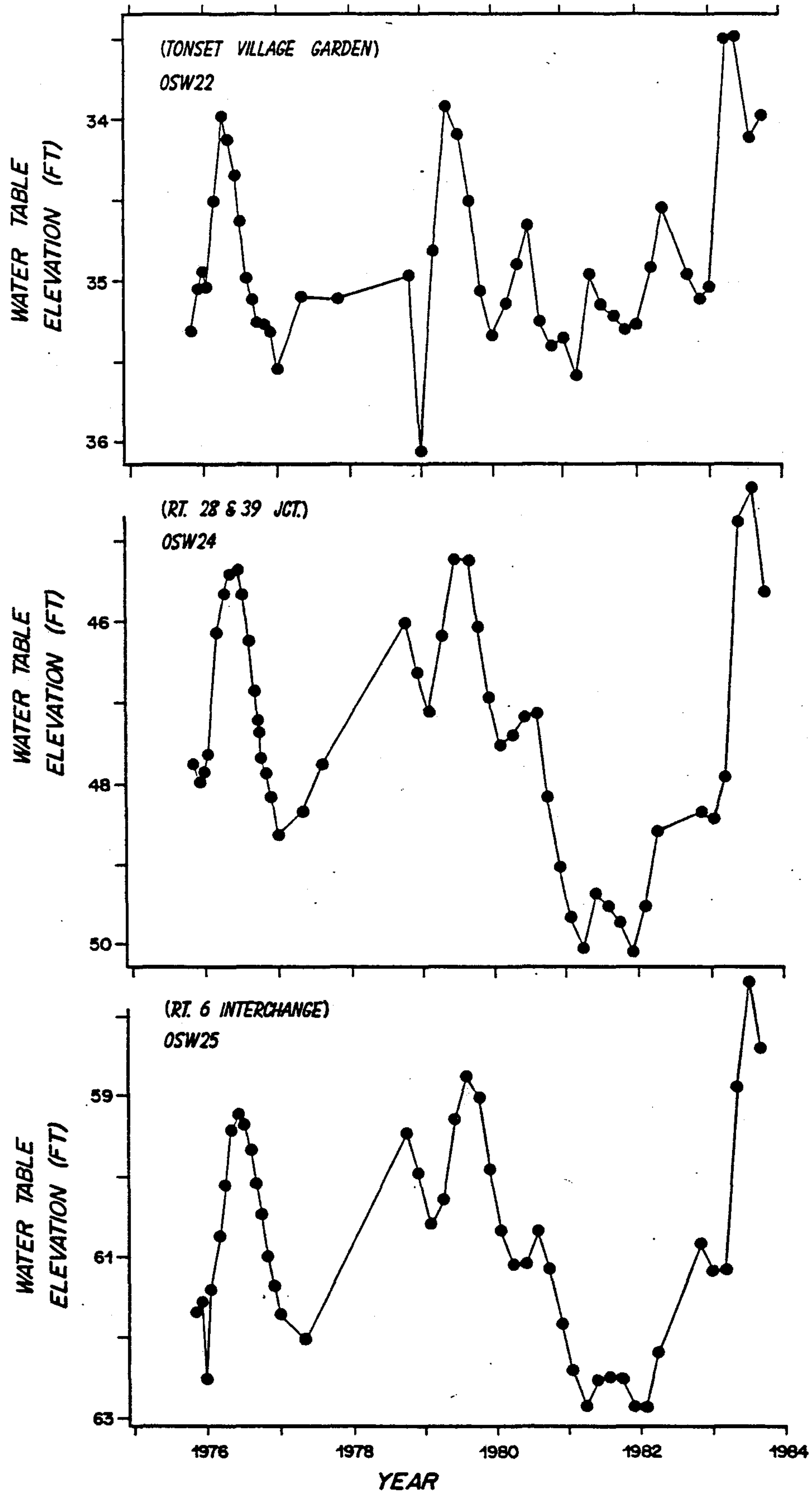

Figure 8. Elevation of the groundwater table in three USGS observation wells in the town of Orleans. OSW 22 is located about 500 meters inland from BW 5 (see Fig. 6). Data from S. Nickerson, Cape Cod Planning and Economic Development Commission.

justified (Guswa and LeBlanc 1981). At the local scale in moraine or ice contact deposits, however, important departures from these assumptions are possible. As result, perched water tables, partially confined aquifers and other deviations from the simplest case may occur. The Town Cove area is a case in point. Groundwater emerges from the base of cliffs, beneath saltmarsh deposits and from the intertidal beachface at many places around the Cove and, as described below, we used these natural springs as one means for sampling the groundwater. At one location along the shore, near the Town center area, one of these springs forms a sheetwash across a pebble-cobble pavement sloping to the water's edge. This surface evidently is wide-spread around Town Cove, although elsewhere it is a buried horizon several feet beneath the surface. In installing the Beach Wells we usually penetrated this resistent till horizon (known locally as "hard pan"), in most cases with considerable difficulty. In one instance, at Asa's Landing, we were unable to penetrate it at all. This layer appears to be quite impervious and may partly control the flow of groundwater near Town Cove. At Beach Well 3, located near the Yacht Club (Fig. 6), groundwater flowed continuously from the well against a hydraulic head of about a foot, after penetrating this stratum.

Although variations in precipitation and recharge cause short-term fluctuations in the elevation of the groundwater table, over the long-term discharge to the Cove can be expected to equal the recharge. Estimates of recharge for the Cape Cod area distributed over the recharge area surrounding Town Cove (7.9×10^6 m^2; see Appendix I), this is equivalent to 0.71 to 0.97×10^4 m^3 per day (Table 4). In addition to this natural recharge, piping of water into the Town Cove recharge area from the Town wellfield adds an artificial recharge,

Table 4. Recharge estimates for the Town Cove recharge area. Total recharge includes natural recharge plus artificial recharge resulting from piping of Town well water into the Town Cove recharge area. Nitrogen loading figures are based on groundwater concentrations listed in columns A and B in Table 3, using the assumption that groundwater discharge into Town Cove equals recharge for its recharge area.

Recharge		Natural Recharge (10^4 m^3/day)	Total Recharge (10^4 m^3/day)	Nitrogen Loading (Kg. NO_3-N/day)	
ins	cm			A	B
13	33	0.71	0.94	9.1	15
15	38	0.82	1.0	9.7	16
18	45	0.97	1.2	11.6	19

estimated by Pelsit (CCPEDC, personal communication) at 0.23 X 10^4 m^3. This is added to natural recharge in Table 4. If it is assumed that groundwater discharge into Town Cove equals this recharge, then one estimate of nitrogen loading from this source is obtained using these values and the groundwater nitrate measurements summarized in Table 3.

Groundwater discharge has been directly measured in natural bodies of water using a bell jar-like device, inserted into the sediment, which vents into a limp, plastic bag whose contents can periodically be measured (Bokuniewicz and Zeitlin 1980; Lee 1976; McBride and Pfannkuch 1975). Seepage meters of this kind were deployed along transects perpendicular to the shore in Town Cove, at several locations and dates. The results (Table 5) indicate discharge is variable in both time and space. Nevertheless, although extreme values ranged from 0.5 to 8.5 liters/m^2/hr., values typically lay between 1.0 and 3.0 liters/m^2/day. There was a tendency for discharge to decrease with distance offshore, in agreement with both theory and observations reported elsewhere (Bokuniewicz and Zeitlin 1980; Lee 1976; McBride and Pfannkuch 1975). Unlike the study of Lee (1976), however, we did not see a clear relationship between discharge rate and tidal stage. The mean of 29 short time series was 2.5 liters/m^2/day.

On the basis of studies mentioned above assume discharge was limited to a narrow band along the shoreline in Town Cove. Observations on the salinity and salinity gradient of porewaters in sediment cores from deeper waters of Town Cove by Giblin, in association with this study, and the absence of salinity changes in benthic chambers she deployed in deep water in the Cove, also by Giblin, support this supposition. Using our measured values and variations on the above assumptions, therefore, another estimate of total discharge is

Table 5. Subtidal groundwater discharge measurements in Town Cove, obtained using bell jar seepage meters along transects extending offshore (t = duration of measurement; q = discharge rate in liters per square meter per hour).

Beach Well No. 5
June 29-30, 1983

	Distance from low-tide line (meters)									
	5		10		15		20		25	
Time[1]	t	q	t	q	t	q	t	q	t	q
1350	3.3	1.6	3.3	1.5	4.0	0.7	4.2	1.4	3.3	0.8
1710									0.9	2.6
1805	13.7	0.3	13.7	0.9	13.1	0.9	12.9	0.8	12.8	0.4
0655	2.9	2.0	2.9	4.0	2.9	3.5	2.9	3.9	2.9	1.7
0950	2.1	4.9	2.1	6.0	2.1	6.0	2.1	5.8	2.1	4.6
Mean[2]		2.2		3.1		2.8		3.0		1.6
S.D.		1.9		2.4		2.5		2.3		1.8

Beach Well No. 4
June 29-30, 1983

	Distance from low-tide line (meters)									
	5		10		15		20		25	
Time	t	q	t	q	t	q	t	q	t	q
1315	3.5	3.5[4]	3.5	3.5[4]	3.5	0.7	3.5	0.5	3.5	0.6
1645	16.4	0.4	16.4	0.2[3]	16.4	0.7	16.4	0.5	16.4	0.3
0915	2.3	5.4	2.3	1.1	2.3	0.7	2.3	0.5	2.3	0.6
Mean[2]2		3.1		1.6		0.7		0.5		0.5
S.D.		2.5		1.7		0.02		0.04		0.15

NS No. 9 Site C
July 19, 1983

	Distance from low-tide line (meters)							
	(9)5		(10)9		(7)14		(6)18	
Time	t	q	t	q	t	q	t	q
0855	2.5	4.8	2.5	4.4	2.5	4.0	2.5	1.2
1120	3.6	2.6	no data		no data		3.6	0.4
Mean[2]		3.7		4.4		4.0		0.8
S.D.		1.6		——		——		0.6

Table 5 (continued). Subtidal groundwater discharge measurements in Town Cove, obtained using bell jar seepage meters along transects extending offshore (t = duration of measurement; q = discharge rate in liters per square meter per hour).

RW No. 3, shore site
July 19, 1983

Distance from low-tide line (meters)

	t	q	t	q	t	q	t	q	t	q	t	r
Time												
1225	no data		0.8	0.5	0.8	1.7	0.8	1.2	0.8	2.2	0.8	2.7
Mean[2]		---		---		---		---		---		---
S.D.		---		---		---		---		---		---

NS No. 9, Site A
July 28, 1983

Distance from low-tide line (meters)

	-28		-16		0		3		8		12	
	t	q	t	q	t	q	t	q	t	q	t	q
Time												
0820	0.8	0.7	1.2	1.2	1.2	7.5	1.2	3.1	1.1	3.8	1.1	3.5
1045	no data		no data		2.4	1.1	2.4	2.3	2.4	3.3	2.3	2.4
1320	no data		no data		no data		2.6	0.6	2.6	2.8	2.6	2.3
1450	no data		1.5	15.7	1.5	5.8	1.5	3.8	1.5	4.5	1.5	3.5
Mean[2]		0.7		8.5		4.8		2.4		3.6		2.9
S.D.		---		10.2		3.3		1.3		0.7		0.7

NS No. 9, Site B
July 28, 1983

Distance from low-tide line (meters)

	5		10		15 (sand)		15 (mud)	
	t	q	t	q	t	q	t	q
Time								
0952	1.7	1.6	1.7	2.8	1.7	3.5	1.7	3.0
1304	1.5	1.0	1.5	1.8	no data		1.5	1.9
1440	2.3	4.9	2.3	4.2	2.3	2.8	2.3	1.2
Mean[2]		2.2		2.9		3.1		2.1
S.D.		1.6		1.2		0.5		0.9

[1]Time measurement began.
[2]Unweighted.
[3]Meter damaged; minimum value.
[4]Meter damaged; maximum value.

possible (Table 6). Using average groundwater nitrate concentrations determined earlier groundwater nitrogen loading can again be estimated.

Other data we have collected allows a qualitative estimate of the seasonal cycle of groundwater flow. For a variety of purposes, as mentioned before, we established 8 observation wells, referred to as Beach Wells, around the margin of Town Cove (Fig. 6). These were 10 foot long PVC pipes, with slotted ends, wrapped with fine plastic mesh sand screen, and jetted into the ground. In all cases the sediments penetrated were glacial deposits rather than true beach deposits. In most cases a resistant glacial-till horizon was penetrated within a few feet of the surface. The elevation of the well caps in all cases was quite close to high-tide level.

The elevation of the water table in these wells was monitored over 1982-83, including a set of observations during a tidal cycle. Unfortunately, several of the wells were disturbed or destroyed during the year. Nevertheless, from these observations (Fig. 9) it appears the response of the water table to tidal fluctuations is generally quite small, and in one case, not detectable. In all cases the water table at the margin of Town Cove responded to seasonal fluctuations in the groundwater table elevation, as observed in USGS observation wells elsewhere in Orleans, although with a much reduced amplitude (Fig. 10). From the classical Darcy relationship, which relates groundwater flow to the first power of water table slope, it can be concluded that the seasonal pattern of water table elevation also reflects the seasonal pattern of groundwater discharge into Town Cove. This information suggests our June discharge measurements and the associated nitrogen loading estimates were above the annual average.

Table 6. Groundwater discharge into Town Cove estimated from seepage measurements along transects perpendicular to the shore (see Fig. 6) and assuming discharge is restricted to shallow water.

Maximum Depth (m)	Discharge Area[a] (m^2)	Groundwater Discharge (m^3/day)	Nitrogen Loading (Kg/day)[b] A	B
1.0	0.76×10^6	4.3×10^4	41	68
1.5	0.80 X "	4.7 "	46	75
2.0	0.85 X "	5.0 "	49	80

[a]See Appendix I
[b]Average groundwater nitrate values from Table 3.

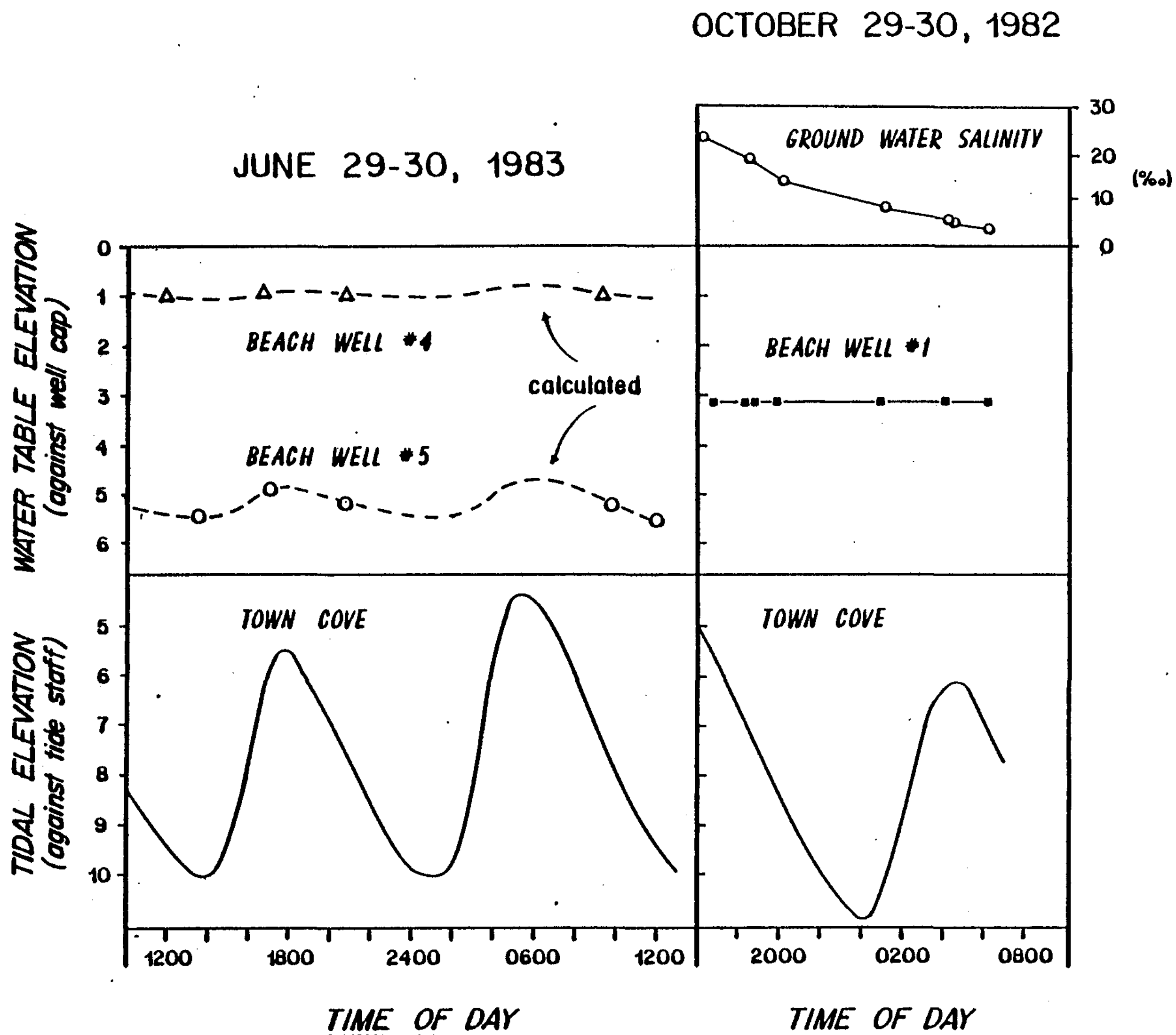

Figure 9. Elevation of groundwater in Town Cove Beach Wells over two tidal cycles, relative to the Town Cove tide, on October 29-30, 1982 and June 29-30, 1983. Salinity data given for October show wash-out of brackish water used to jet the well into the ground. All wells were located near the high tide line.

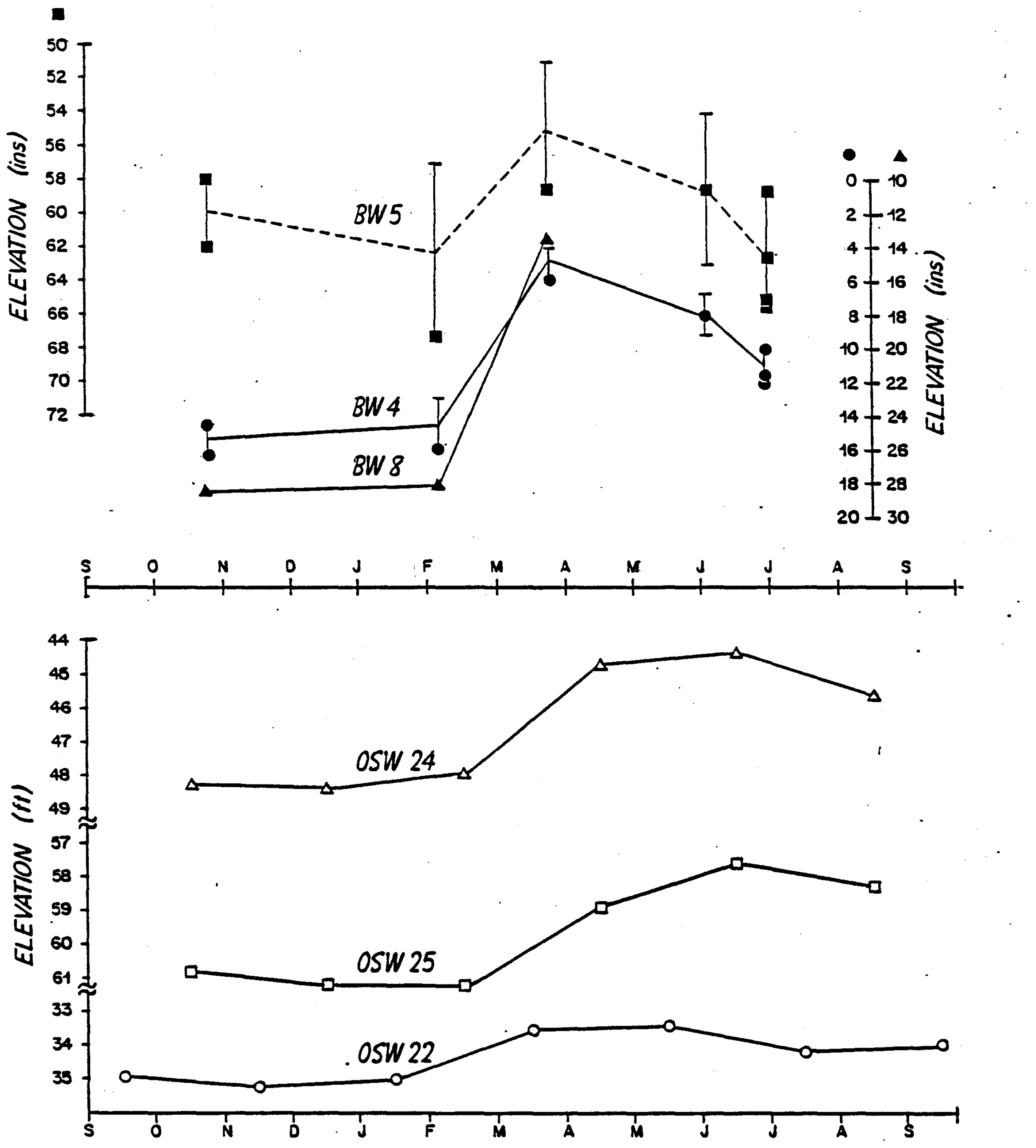

Figure 10. Annual fluctuations of the groundwater elevation in Town Cove Beach Wells and in USGS observation wells in the Town of Orleans between September 1982 and September 1983. Note the difference in elevation scales. USGS well data from S. Nickerson, Cape Cod Planning and Economic Development Commission.

2. Streams and Surface Run-off

Although only a small portion of total precipitation remains as surface run-off from the soils of Cape Cod, perhaps 3 to 9 inches (Strahler, 1972), paved roads and other surfaces can effectively increase that amount. Three conspicuous storm sewer pipes enter Town Cove - near the Town Shellfish Hatchery near BW 1 (Fig. 6); at the head of Town Cove near the Yacht Club; and at Asa's Landing -- additional storm sewers debouch at Cottage Street, and at various sites along the Eastham shore of Town Cove. Many of the storm sewers in Orleans drain into natural leaching beds, contributing water and dissolved materials to the groundwater.

Average daily contributions of run-off to freshwater discharge are tabulated in Table 7. It should be stressed that, unlike groundwater, run-off is delivered extremely unevenly in time. In 1982-1983, 15% of the annual precipitation came in two rain events over a two day period (NWS, 1982-83). Even after the 4.56 inch rainfall of September 2, 1982, most storm sewers had stopped running within a few hours. If 10% of this rainfall entered Town Cove as run-off, in addition to that falling directly on the estuary, the amount of freshwater involved would be about 25 X 10^4 m^3, which is roughly four times our maximum daily estimate for groundwater discharge. Determinations of nitrate and ammonia content of storm water, taken at Gutter Pond and at the Main Street storm sewer outlet (total nitrogen of 0.06 ppm and 0.06 ppm, respectively) during this rain event, suggest the nitrogen input to Town Cove from run-off of this one storm would have been 5 kg.

CCPEDC (1976) gives nitrogen analyses for storm water at various sites on Cape Cod. Their mean of 19 values for nitrate plus ammonia is 2.5 ppm

Table 7. Estimated daily freshwater input to Town Cove from surface runoff for three runoff levels. Nitrogen loading to Town Cove is based on discharge volumes and the average stormwater nitrogen content from data in Table 8, 1.11 ppm.

Amount of Runoff ins	cm	Runoff Volume (10^4 m^3/day)	Nitrogen Loading (Kg/day)
2.8	7.1	0.15	1.6
8.8	22	0.48	5.3
11.3	29	0.62	6.8

Table 8. Analyses of nitrogen species in storm water and water from Gutter Pond, Orleans, Massachusetts.

Date	Nitrate (ppm-N)	Ammonia (ppm-N)	Total N (ppm-N)	Rainfall (ins)
Main Street Sewer				
August 18, 1982				0.03
(11:25)	2.31	0.85	3.16	
(")	2.44	0.85	3.29	
(11:50)	1.33	0.53	1.86	
(")	1.35	0.53	1.88	
September 2, 1982	0.06	0.00	0.06	4.52
Asa's Landing				
June 28, 1983	0.30	0.48	0.78	
Gutter Pond				
August 6, 1982	0.13		(1.53)[a]	0.00
August 11, 1982		0.43		0.05
August 27, 1982	0.10	-	(1.30)[a]	0.0t
September 2, 1982	0.04	0.02	0.06	4.52
February 2, 1983	0.43			0.00
February 4, 1983	0.36	0.25	0.61	0.02
June 3, 1983	0.0	1.09	1.09	0.00
June 28, 1983	0.38	0.49	0.87	1.36
June 29, 1983	0.22	1.46	1.68	0.00
June 30, 1983	0.47	1.85	2.31	0.00
		Mean[b]	1.11	

[a]Nitrate, ammonia plus organic nitrogen
[b]Using data from rainy days only

nitrogen. Concentrations vary from 0.5 to 13 ppm. Our analyses of storm water (Table 8) indicate a range from 0.06 ppm after the torrential rain of September 2, 1982, to 3.86 ppm accompanying initial discharge of a light rain in August 1982, sampled at the Main Street storm sewer outlet. Successive analyses during the rainfall showed a decrease in total nitrogen by 56% in 25 minutes. Had the rain continued, nitrogen could rapidly have reached the low level observed after the September 2 storm, 0.06 ppm.

Although there are no streams, proper, entering Town Cove, there is a permanent flow from the site of Jeremiah's Gutter near the Town Hatchery (Fig. 6), now the site of two small ponds, from which the effluent drains under the highway in a sewer pipe to Town Cove. A check valve at the Cove end of this pipe does not appreciably retard the tide from entering the pipe, with the result that the lower Gutter Pond is shows semi-diurnal tides and upper Gutter Pond, at a higher elevation, is regularly inundated.

On June 29, 1983 a 90° "V" notch wire was installed in the pipe draining upper Gutter Pond. Over a period of about 12 hours the flow remained about constant, which along with its depressed temperature (16°C) suggests it consisted primarily of groundwater. Discharge was estimated using the "cone formula" (U.S. Department of Interior 1974) at 0.037×10^4 m^3/day. From the elevation of the groundwater table at this time, it can be surmised that this flow rate was slightly higher than the average for the year, periods of run-off excepted. Water samples collected initially and again after the 12 hour measurement period contained an average of 2.01 ppm-N (nitrate plus ammonia). This indicates nitrogen loading to Town Cove at this time was 0.77 Kg/day from Gutter Pond.

3. Total Freshwater Discharge

An approach we used in estimating total freshwater discharge into Town Cove employed the method used by Goldman and Dennett (this report) for estimating the flux of dissolved and suspended materials in Cove water. Time series of the concentration of these variables (e.g., see Fig. 11), along with information on tidal displacements provided by Aubrey (this report) permit estimates of freshwater tidal fluxes and their difference, the net freshwater tidal flux. Using this method, it is necessary to assume steady state conditions within the Cove, unless data are available to correct for changes in the variable of interest. The flux of fresh water determined in this manner for four dates (Table 9) indicates both net fresh water exports as well as net import to Town Cove. On dates when rain fell during our fieldwork (April and August), the outer Nauset embayment evidently served as a precipitation trap and ultimately as a source of fresh water to the Cove. This diminished or reversed the flux of freshwater and it suggests nutrients and potential pollutants entering the outer embayment can be transported into Town Cove.

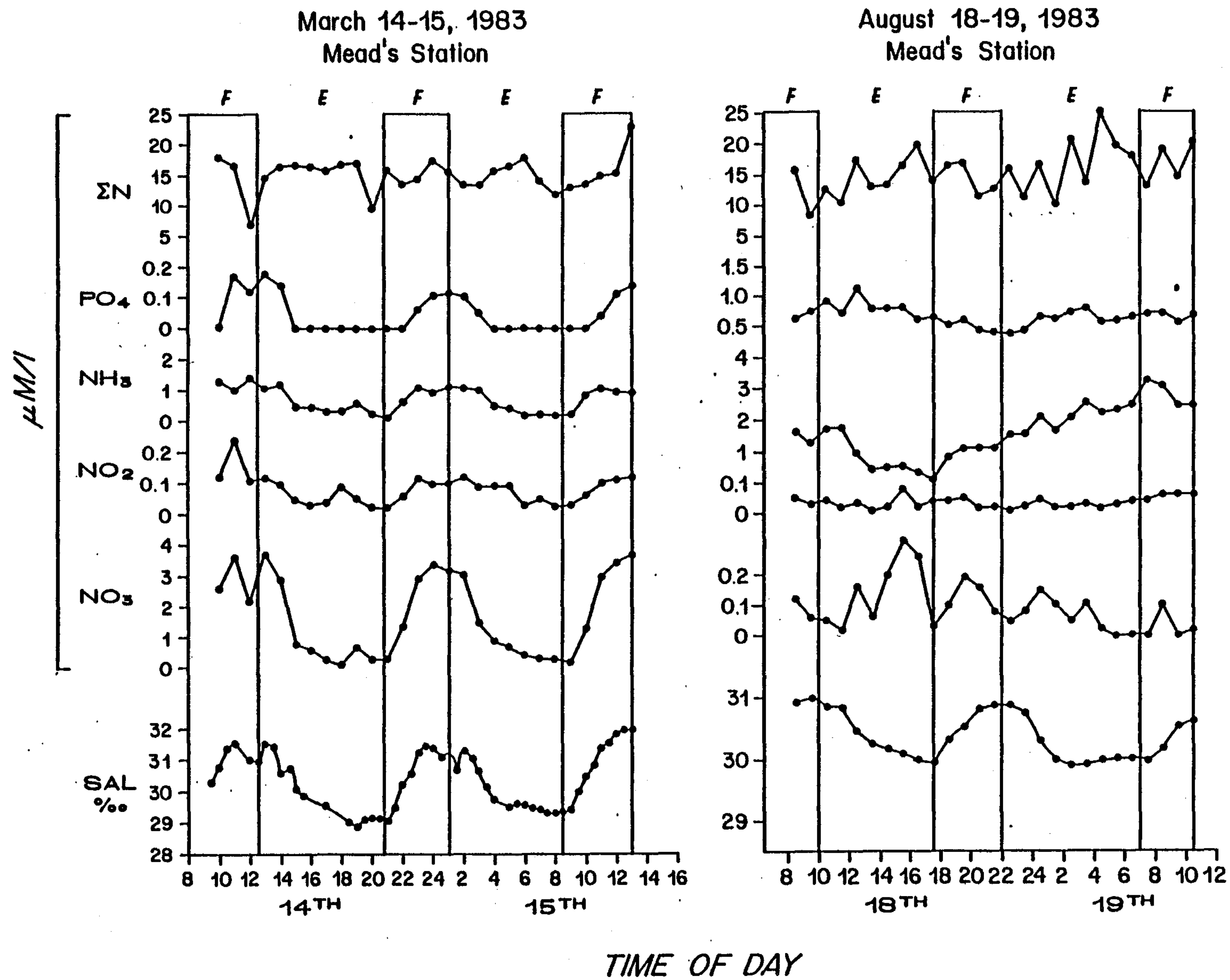

Figure 11. Time series of salinity (units of parts per thousand) measured over two tidal cycles at Mead's Station on March 14-15, 1983 and August 18-19, 1983. Other variables shown are nitrate, nitrite, ammonia and total nitrogen (units of uM/l).

Table 9. Freshwater fluxes past Mead's Station, based on salinity time series and tidal information.

Date	Tidal Flux (10^4 m^3/day) Flood	Ebb	Flood	Ebb	Net Daily Discharge[1]
March 14-15, 1983	6.9	14	6.4	12	8.9
April 26-27, 1983	6.1	6.7	6.9	6.6	-0.2
June 29-30, 1983	1.1	3.2	0.9	3.5	4.1
August 18-19, 1983	0.19	0.14	0.14	0.20	0.05

[1]Corrected for net changes in tide level, and expressed over 24 hours.

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Nitrogen - Plant Dynamics

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Department of Biology

A. Introduction

Over the past year we have performed a series of biological and chemical measurements in Town Cove, Orleans to determine the relative impact of ground-water nitrogen on aquatic primary productivity in the cove basin. These studies have been performed in conjunction with other studies on groundwater hydraulics and chemistry, benthic nutrient dynamics, denitrification, and physical modelling of tidal exchange. The overall goals of our part of the study have been to determine the extent of cultural eutrophication on water quality in Town Cove and to determine component nutrient fluxes that would be included in a systematic mass balance of nitrogen and other constituents in the cove.

Our efforts have involved a number of approaches, all aimed at meeting the above goals. Specifically, our project involved four types of studies: characterization of nutrient and chlorophyll distributions in Town Cove, estimates of seasonal primary productivity, use of several types of nutrient bioassays and other indices of nutrient limitation to determine the nutrient status of the cove, and development of a nutrient and biomass mass balance based on tidal exchange at the entrance to the cove.

B. Nutrient, Chlorophyll and Biomass Distributions

We established a grid of sampling stations in the cove at the start of the project (Fig. 12) and carried out an extensive sampling program over the first

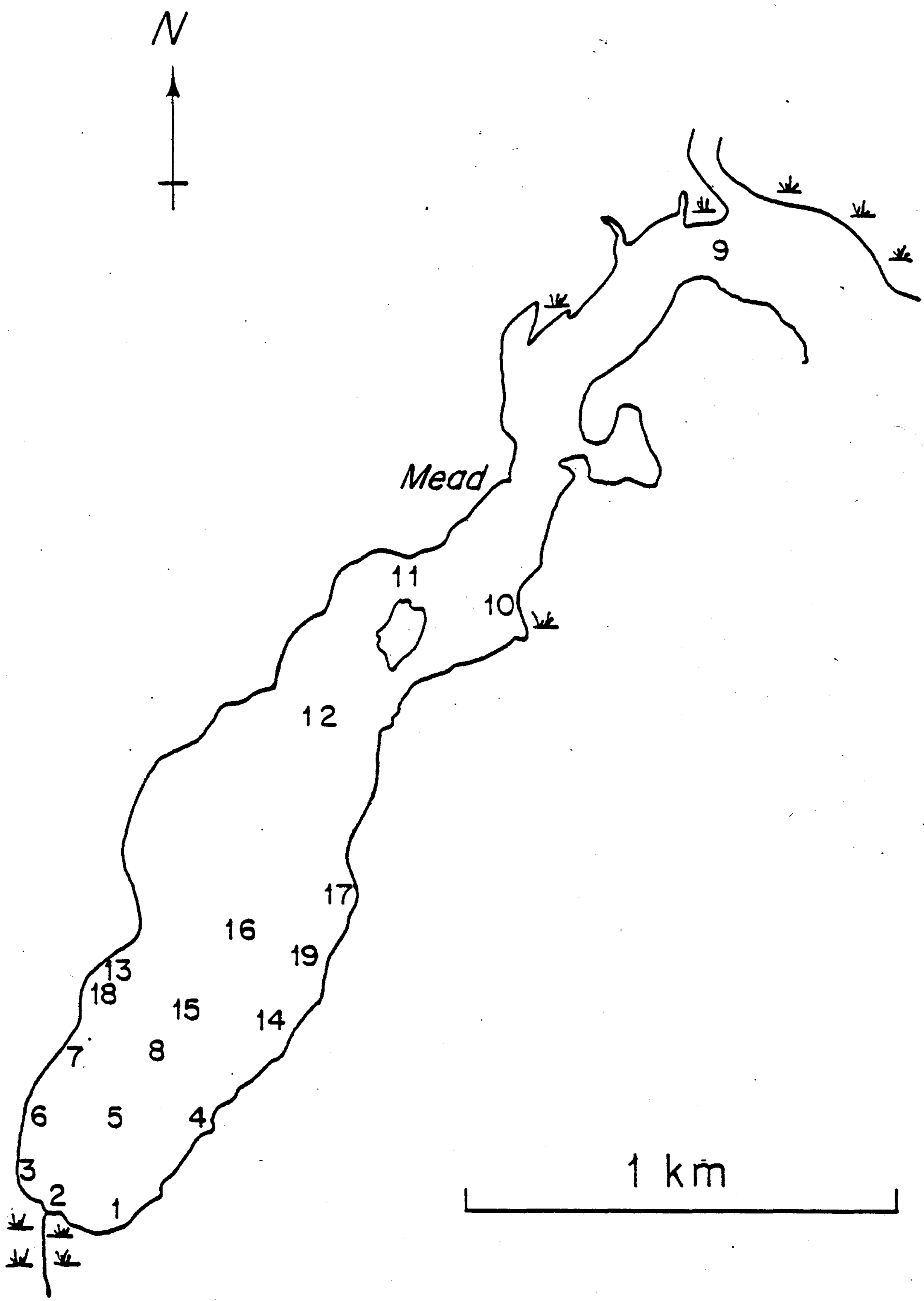


Figure 12. The location of biological sampling stations, Town Cove, Cape Cod, Mass.

six months, mapping the distribution of both nutrients (NH_4^+, urea, NO_3^-, NO_2^-, PO_4^{-3}) and chlorophyll a (a chemical constituent unique to plants) on a seasonal basis. Overall, we found a consistent pattern through December, 1982 that the sum of dissolved inorganic nitrogen plus urea ($\Sigma N = NH_4^+ + NO_3^- + NO_2^-$ + urea) along with PO_4^{-3} generally were highest along the shore, particularly near the Orleans Yacht Club, and lowest in the center of the cove (Tables 10 and 11 and Fig. 13). Chlorophyll a concentrations, however, were high at virtually all sampling stations (Compare data from Station 8 in Fig. 13 with other shore stations).

What is most apparent in Fig. 13 is that no clear relationship existed during the sampling period between nutrient and chlorophyll a concentrations in the cove, particularly along the shore (Stations 3, 6, & 17). ΣN concentrations in these locations ranged from 0.3 ug atoms/liter to 8.3 ug atoms/liter, whereas chlorophyll a levels varied irregularly between 1.1 ug/liter and 22.0 ug/liter. A more constant trend of low and variable nutrients, but high chlorophyll a was found in the center of the cove (Station 8).

There also was no apparent trend in the distribution of the forms of dissolved nitrogen in the cove. Both NH_4^+ and urea frequently were as important as NO_3^- and NO_2^-. Of particular interest, chlorophyll a levels were relatively high at all four stations in the cove during winter (December 7-9, 1982), ranging from 2.5 ug/liter at Station 17 to 5.5 ug/liter at Station 3. At the same time ΣN concentrations during this period were uniformly low (<2.5 ug atoms/liter) at all four stations.

When it became apparent that nutrient and chlorophyll a concentrations fluctuated so significantly, we abandoned our routine sampling program in

Table 10. Summary of nutrient and biomass data collected in Town Cove, Orleans on July 27, 1982.

Location	Station	Particulate Carbon (ug/l)	Particulate Nitrogen (ug/l)	PC:PN Ratio (wt:wt)	Chla (ug/l)	NH_4^+ (ug at/l)	$NO_3^-+NO_2^-$ (ug at/l)	Urea (ug at/l)	ΣN (ug at/l)	PO_4^{-3} (ug at/l)	$\Sigma N:P$ Ratio (by atoms)
Shore-line Lower Cove	17	4870	521	9.3	22.0	0.43	0.31	0.69	6.43	0.92	7.0
	14	1424	324	4.4	2.1	0.44	1.32	0.63	2.39	1.14	2.1
	4	1136	172	6.6	1.0	0.66	0.74	0.67	2.10	0.82	2.5
	1	59500	4170	14.3	95.9	0.86	0.17	1.50	2.53	5.76	0.4
	2	10980	1061	10.3	16.9	0.86	6.55	1.05	8.46	4.58	1.8
	3	3170	381	8.3	3.6	0.55	4.92	0.76	6.23	1.25	5.0
	6	1460	250	5.8	1.3	0.42	1.79	0.71	2.92	0.92	3.2
	7	1561	217	7.2	2.9	0.32	0.27	0.71	1.30	1.21	1.1
	13	1991	103	19.3	5.1	14.10	2.40	0.07	16.57	0.30	55.2
Shore-line Upper Cove	10	1779	236	7.5	2.6	0.55	0.10	1.46	2.11	0.99	2.1
	11	1669	173	9.4	3.1	<0.03	0.04	0.44	0.51	0.86	0.6
Cove Inlet	9	1653	209	7.9	2.5	0.22	0.04	0.52	0.78	0.53	1.5
Cove Center	12	1117	61	18.3	1.6	1.56	0.04	0.59	2.19	0.81	2.7
	16A*	1476	187	7.9	2.0	0.35	<0.03	0.83	1.21	0.39	3.1
	16B**	1818	215	8.5	3.6	0.70	<0.03	0.73	1.46	0.57	2.6
	16C***	1649	217	7.6	2.2	0.43	<0.03	0.91	1.37	0.33	4.2
	15A	1493	241	6.2	2.8	0.35	0.03	0.51	0.89	0.35	2.5
	15B	1706	172	9.9	4.8	0.45	0.06	0.21	0.72	0.57	1.3
	15C	2530	319	7.9	6.7	0.38	0.03	0.79	1.20	0.55	2.2
	8	3480	305	11.4	5.2	0.27	0.06	0.91	1.24	0.29	4.3
	5A	5160	455	11.3	9.9	0.55	0.08	0.83	1.46	0.29	5.0
	5B	1469	266	5.5	2.4	0.38	0.03	0.92	1.33	1.02	1.3
	5C	2560	274	9.3	3.2	0.24	0.05	0.47	0.76	0.28	2.7

*Surface sample
**Mid-depth sample
***Bottom sample

[-42-]

Table 11. Summary of nutrient and chlorophyll data collected in Town Cove, Orleans on August 11, 1982 and September 9, 1982.

Location	Station	chl a (ug/l)		NH_4^+ (ug at/l)		$NO_3^-+NO_2^-$ (ug at/l)		Urea (ug at/l)		ΣN (ug at/l)		PO_4^{-3} (ug at/l)		ΣN:P (by atoms)	
		8/11	9/24	8/22	9/24	8/11	9/24	8/11	9/24	8/11	9/24	8/11	9/24	8/11	9/24
Shore-line	17	-	1.5	-	-	-	-	-	-	-	-	-	-	-	-
	19	2.5	0.9	2.14	-	15.40	-	0.41	-	17.95	-	1.14	-	15.7	-
	14	2.8	2.5	0.54	-	3.84	-	0.42	-	4.80	-	1.0	-	4.8	-
	4	1.8	0.6	0.24	1.19	3.35	12.10	0.53	0.30	4.12	13.59	0.80	1.02	5.2	13.3
	1	1.8	1.5	0.33	1.59	0.62	<0.03	0.51	1.05	1.46	2.67	0.52	0.83	2.8	3.2
	2	0.9	0.4	9.41	5.13	13.10	7.60	0.13	2.24	22.64	14.97	3.58	2.49	6.3	6.0
	3	-	1.1	-	3.24	-	0.19	-	0.39	-	3.82	-	0.93	-	4.1
	6	2.9	2.5	0.17	1.37	6.44	1.50	0.25	0.44	6.86	3.31	0.03	0.65	22.9	5.1
	7	2.1	2.2	0.30	1.02	10.18	2.80	0.65	0.32	11.13	4.14	0.36	0.60	30.9	6.9
	18	1.0	3.7	1.84	-	0.09	-	0.23	-	2.16	-	0.73	-	3.0	-
	13	0.2	1.7	30.38	51.83	-	14.30	-	3.77	-		1.14	0.31	-	100.2
Shore-line	10	-	2.0	-	0.20	-	0.17	-	0.46	-	0.83	-	0.41	-	2.0
Upper Cove	11	-	4.6	-	0.89		<0.03	-	0.15	-	1.07	-	0.64	-	1.7
Cove Inlet	9	2.6	0.8	0.07	0.13	-	0.05	-	0.50	-	0.68	0.53	0.54	-	1.3
Cove Center	12	-	0.9	-	0.39	-	<0.03	-	0.49	-	0.91	-	0.79	-	1.2
	8	3.6	3.4	0.22	0.06	-	0.33	-	<0.03	-	0.42	0.09	0.49	-	0.9
	5	3.1	3.3	0.29	0.25	0.18	2.60	0.52	0.05	0.99	2.90	0.17	0.49	5.8	5.9

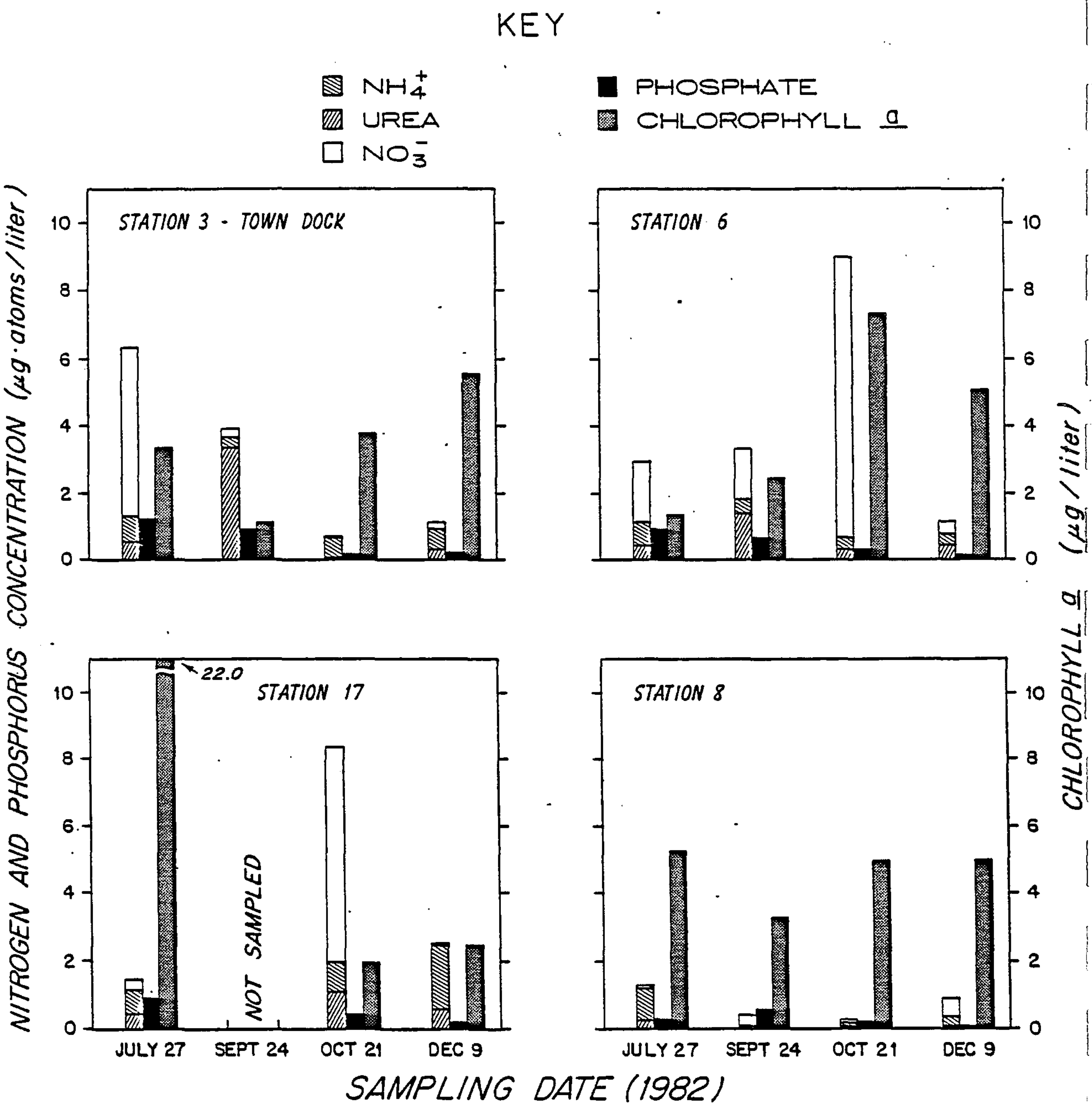


Figure 13. Nutrient and chlorophyll data for surface water samples from Town Cove, Cape Cod, Mass, July 27, September 24, October 21 and December 9, 1982 (see Fig. 12 for station locations).

December, 1982. We recognized at that time that measurements of dissolved nutrients and chlorophyll in the water column were poor indicators of biological activity in Town Cove for at least two reasons. First, along the shore where there is significant groundwater input of nutrients, the temporal and spatial distributions of such nutrients in the water column always will be highly heterogeneous; thus only through a very rigorous and elaborate sampling program would it have been possible to detect any relationship (if any) between nutrient concentration and chlorophyll levels. Such a program was beyond the limits of our project.

Second, although NO_3^- usually is the major source of groundwater nitrogen entering the cove, the uptake and conversion of oxidized nitrogen (NO_3^-) to reduced forms (NH_4^+) occurs at rapid rates through biologically mediated reactions. In addition, some portion of available inorganic nitrogen continually is converted to plant and algal biomass. Thus measurement of ambient concentrations of nutrients and chlorophyll provide no clue as to the magnitude of the rates of conversion of nitrogen between chemical and biological forms.

We did, however, continue to measure nutrients, chlorophyll a, particulate carbon (PC), and particulate nitrogen (PN) at Station 3 and at Station 9 (the cove inlet) over the entire project period in conjunction with our primary productivity studies (described below). Samples generally were collected between 8 AM and 10 AM of each study day. As summarized in Table 12, the irregular trends in nutrient and chlorophyll concentrations we observed within the cove between July, 1982 and December, 1982 (Fig. 13) continued through August, 1983. Inlet concentrations of all measured constituents tended to be a little lower than at Station 3, however. But, as will be shown subsequently, there were

Table 12. Summary of seasonal measurements of dissolved nutrient and particulate constituents at the inlet and at Station 3 along the shore of Town Cove, Orleans during 1982-1983.

Constituent	08/11/82	09/20/82	10/20/82	10/21/82	12/07/82	02/16/83	05/18/83	08/05/83
Town Cove (Station 3)								
Chl *a* (ug/l)	3.6	1.1	2.2	3.3	5.5	2.0	2.9	1.3
PO_4^{-3} (ug at/l)	0.09	0.93	0.47	0.17	0.22	0.33	0.22	1.87
NH_4^+ (ug at/l)	0.22	3.24	1.04	0.07	0.31	2.16	0.07	1.53
$NO_3^-+NO_2^-$ (ug at/l)	-	0.19	0.30	-	0.17	6.42	1.22	0.23
Urea (ug at/l)	-	0.39	3.78	0.61	0.62	0.83	0.60	0.64
SN (ug at/l)	-	3.82	5.12	-	1.10	9.41	1.89	2.40
SN:P Ratio (by atoms)		4.1	10.9		5.0	28.5	8.6	1.3
PN (ug/l)	271	123	106	124	19	99	162	193
PC (ug/l)	1100	515	711	728	102	702	1150	1032
PC:PN Ratio (wt:wt)	4.1	4.2	6.7	5.9	5.5	7.1	7.1	5.3
Inlet (Station 9)								
Chl *a* (ug/l)	2.6	0.8	2.0	1.6	6.1	-	1.5	0.8
PO_4^{-3} (ug at/l)	0.53	0.54	0.27	0.31	0.06	-	0.23	0.89
NH_4^+ (ug at/l)	0.07	0.13	1.03	1.12	0.03	-	0.14	1.75
$NO_3^-+NO_2^-$ (ug at/l)	-	0.06	0.61	0.23	0.10	-	0.23	0.27
Urea (ug at/l)	-	0.50	0.06	0.32	0.29	-	0.18	0.75
SN (ug at/l)	-	0.69	1.70	1.67	0.42	-	0.55	2.77
SN:P Ratio (by atoms)		1.3	6.3	5.4	7.0		2.4	3.1
PN (ug/l)	135	104	83	76	99	-	121	111
PC (ug/l)	667	413	637	649	545	-	613	614
PC:PN Ratio (wt:wt)	4.9	4.0	7.7	8.5	5.5	-	5.1	5.5

tremendous tidal influences on the concentration of particulate constituents at the cove entrance. Thus the differences we measured between cove and inlet biomass concentrations had little relevance because they were based on samples always collected at the same time of day. Tidal influence, was, therefore, another key factor that negated the utility of carrying out nutrient and biomass measurements on grab samples from designated locations.

One important conclusion that can be drawn from the nutrient and chlorophyll data is that in comparison to nearby coastal waters, Town Cove is enriched year around in both chlorophyll and particulate biomass. As summarized in Table 13, chlorophyll and particulate material in Town Cove during both winter and summer is significantly greater than in the nearby coastal water, Vineyard Sound, even though dissolved nitrogen concentrations in both locations are comparable. The Vineyard Sound data was derived from a long term study conducted on nutrient dynamics in coastal waters in the laboratory of J.C. Goldman. These results once again point out the lack of correlation between nutrient and biomass data and the futility of using ambient nutrient data in a diagnostic fashion to estimate the degree of eutrophication in water body.

C. Primary Productivity Measurements

In an attempt to characterize the intensity of seasonal primary productivity in Town Cove in relationship to the quantity of algae present, we performed a series of bottle incubation studies using labelled $H^{14}CO_3^-$ as a tracer of photosynthetic activity. A total of 8 studies were performed between August 11, 1982 and August 5, 1983 with an incubation system designed specifically for primary productivity measurements. The system consists of 12 one

Table 13. Comparison of typical winter and summer nutrient and biomass data in Town Cove, Orleans and Vineyard Sound, Massachusetts.

Constituent	December			August			
	Town Cove	Station 9	Vineyard Sound (1979)	Town Cove	Station 9	Vineyard Sou[illegible] (1979)	(198[illegible]
Chl *a* (ug/l)	5.5	6.1	1.5	1.3	0.8	1.0	0.[illegible]
NH_4^+ (ug at/l)	0.31	0.03	0.10	1.53	1.75	0.05	0.30
$NO_3^-+NO_2^-$ (ug at/l)	0.17	0.10	1.30	0.23	0.27	0.23	0.30
PN (ug/l)	19	99	59	193	111	39	45
PC (ug/l)	102	545	325	1032	614	296	406
PC:PN Ratio (wt:wt)	5.5	5.5	5.5	5.3	5.5	7.6	9.0

liter glass vessels, each with a water jacket for temperature control (established by circulating ambient water through the jackets), and each mixed continuously with a battery operated magnetic mixer. Different light levels were simulated by wrapping neutral density screening around the vessels.

The incubations were initiated between 9AM and 10AM of each study day by adding $H^{14}CO_3^-$ to the samples; subsamples were then taken over the course of the incubation, which usually lasted for 4-5 hours, and were processed for measurement of radioactivity. Rates of inorganic carbon fixation (rates of primary production) were calculated from the slopes of the resulting uptake curves. With the exception of one experiment (February, 16, 1983), concurrent incubations were run on samples from the cove inlet (Station 9) and from the cove itself (Station 8 on August 8, 1982 and September 20, 1982 and Station 3 on the other dates). Only Station 3 was sampled on February 16, 1983.

For each incubation we determined both the rate of absolute primary productivity P (ug C/l/hr) and the associated Assimilation Number A (ug C/ug Chl a/hr). The Assimilation Number is a good indicator of how fast an algal population is photosynthesizing because it normalizes the rate of absolute productivity to the amount of algal biomass present (represented by the chlorophyll concentration). In general, values of A in the range 20-35 represent algal populations that are growing vigorously and are not nutrient limited. The number is temperature-sensitive so that lower values would be expected during winter months. For experiments in which we compared productivity at the inlet (Station 9) and Stations 8 or 3 that were in the cove, we determined three biological ratios from the incubation data. These ratios, f, R_P, and R_A, are, respectively, the ratios of chlorophyll a concentration, P, and A, from the cove and from the cove inlet.

The data for the productivity studies are summarized in Table 14, and typical uptake curves are presented in Fig. 14. Although we measured productivity over a wide range of simulated light intensities (to represent productivity as a function of water depth), we only reported productivity estimates from full sunlight (100% incident irradiance) incubations and from the light level for which maximum photosynthesis was measured. We had no control over the weather conditions on the sampling dates and thus several of the 1982 experiments during summer and fall were performed during cloudy days. As a result, peak productivity at both the inlet and cove stations occurred between the surface and the 60% light level in the August 11 through October 21, 1982 experiments. Under winter conditions, however, inhibition of surface productivity developed so that peak productivity occurred at the 30% light level in December and down to the 5% light level in February. During the May and August, 1983 studies, which happened to be performed on sunny days, peak productivity occurred at the 30% light level.

In general, values of both f and R_P were greater than 1.0 indicating that the higher chlorophyll concentrations within the cove relative to the inlet led to correspondingly higher rates of absolute productivity within the cove. Values of R_P during August of both 1982 and 1983 were, however, less than 1.0, suggesting that algal blooms had developed in the cove earlier in the summer and were in the final stages of activity. Based on the consistently low values of R_A (always close to or less than 1.0), we can conclude that, although there does appear to be somewhat higher levels of productivity in the cove relative to the inlet (except during late summer), algal activity in both locations are comparable. Moreover, the very high assimilation ratios A found throughout the

Table 14. Summary of primary productivity experiments in Town Cove, Orleans, August 1982-August 1983.

Date	Temp. (°C)	Incident Irradiance (W/m^2)	(%)	Cove[a] Chl a (ug/l)	Cove[a] P (ugC/l/hr)	Cove[a] A[c]	Inlet[b] Chl a (ug/l)	Inlet[b] P (ugC/l/hr)	Inlet[b] A	f[d]	R_P[e]	R_A[f]
Aug. 11, 1982	20-22	2237	100	3.60	90.2	25.1	2.57	105.8	41.2	1.40	0.85	0.61
			60		105.0	29.2		96.0	37.4		1.09	0.78
Sept. 20, 1982	17	1005	100	1.55	32.0	20.6	0.74	15.3	20.7	2.09	2.09	1.00
			60		32.8	21.2		11.2	15.1		2.93	1.40
Oct. 20, 1982	12	3882	100	1.75	26.3	15.0	1.68	25.9	15.4	1.04	1.02	0.07
			60		28.4	16.2		21.9	13.0		1.30	1.25
Oct. 21, 1982	13	2815	100	4.92	49.5	10.1	1.56	28.0	17.9	3.15	1.77	0.56
			60		44.3	9.0		22.3	14.3		1.99	0.63
Dec. 7, 1982	11-12	2075	100	5.54	26.4	4.8	6.07	23.7	3.9	0.91	1.11	1.23
			60		83.8	15.1		29.2	4.8		2.87	3.14
Feb. 16, 1983	1	3591	100	1.96	6.9	0.5	-	-	-	-	-	-
			5		13.3	6.9	-	-	-	-	-	-
May 18, 1983	10.5-11.5	7680	100	2.89	6.0	2.1	1.52	5.7	3.8	1.90	1.05	0.55
			30		52.9	18.3		27.8	18.3		1.90	1.00
Aug. 5, 1983	23-24	6475	100	1.34	6.6	4.9	0.83	18.5	22.3	1.61	0.36	0.22
			30		29.0	21.6		40.3	48.6		0.72	0.44

[a]Cove sampling point was Station 8, on August 11 and September 20 and Station 3 on the other dates.
[b]Inlet sampling point was Station 9.
[c]Assimilation ratio - ugC/ g Chl *a*/hr.
[d]Cove Chl *a*· Inlet Chl *a*.
[e]Cove P· Inlet P.
[f]Cove A· Inlet A.

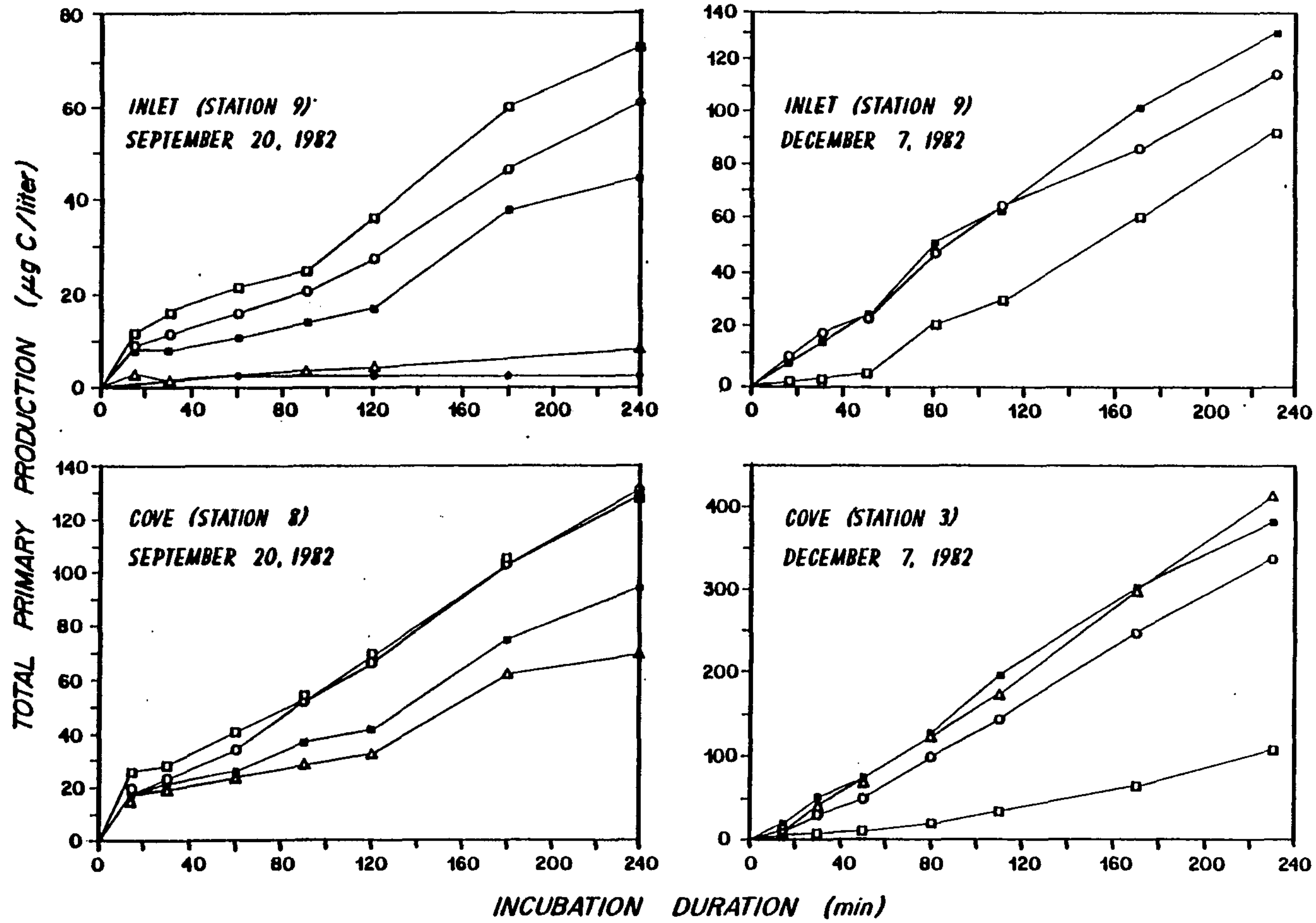


Figure 14. Typical primary productivity uptake curves for incubations performed on September 20 and December 7, 1982. □ = 90% light; ○ = 60% light; ■ = 35% light; △ = 20% light; ● = dark control.

most of the year (15 to >40, except during late winter) provide strong evidence that rates of algal primary productivity in the entire cove are not nutrient-limited and are close to the maximum possible for the prevailing environmental conditions (i.e., sunlight and temperature).

D. Indices of Nitrogen Limitation

In trying to assess the impact of anthropogenic nitrogen input on primary productivity in Town Cove it is necessary to distinguish between nutrient limitation of algal growth rate and nutrient limitation of total algal yield. The first type of relationship describes the effect of nutrient availability on the physiological state of the algal population (i.e., are they growing fast or slow) and the second relationship provides an estimate of the net algal biomass that can be supported in a water body regardless of the speed at which algal growth proceeds. In practice, it is difficult to separate these two effects experimentally because many types of competing biological activities are occurring concomitant with algal growth. For example, algal growth is, to varying degrees, balanced by zooplankton and other heterotrophic grazing. Under such conditions nutrients are recycled within the water column so that it is possible to have very high algal growth rates, but little net accumulation of algal biomass. Large increases in algal biomass resulting from nutrient input occur when algal growth is uncoupled from and much more rapid than zooplankton grazing. Such a situation is commonly referred to as eutrophication of a water body.

There are a variety of experimental techniques for testing whether a water body is nutrient limited or not. None, however, are foolproof for providing a clear answer to the question of how much algal biomass will result from a given input of anthropogenic nutrients. Our approach in this study has been to use a variety of techniques to address this question. Specifically, the techniques included: 1). comparisons of dissolved and particulate nutrient ratios (e.g., PC:PN, dissolved ΣN:P) from Town Cove samples with established values representative of nutrient and non-nutrient limiting conditions, 2) EPA-type nutrient enrichment bioassays, 3) bioassays to test for dark CO_2 uptake in the presence presence or absence of NH_4^+ enrichment, and 4) nitrogen uptake bioassays using the stable isotope ^{15}N. Results from these studies were used collectively to determine the degree of nitrogen-limitation of both growth rate and algal yield in Town Cove.

1. Nutrient Ratios. It is well established that under conditions of excess nutrients the chemical composition of algae is remarkably constant: about 50% carbon, 8-10% nitrogen, and <1% phosphorus (represented by a carbon: nitrgen ratio of 5 by atoms or 6 by weight and a nitrogen:phosphorus ratio of 15 by atoms in the algal biomass). The chemistry of algal biomass can then be described by ratios of the three major chemical components, of which the PC:PN and ΣN:P ratios are the most commonly used. This indicates that algae assimilate available nutrients from the water in certain ratios and that to some degree the ratios by which nutrients are found in the water column reflect the ratios of these nutrients in algal biomass. Thus a PC:PN ratio in algal biomass of 4-7 (by weight) is one indication that nitrogen does not limit algal growth. Similarly, a ΣN:P ratio in the ambient water of <15 represents non-phosphorus limitation. Although we did not systematically measure the ratios of PC:PN and ΣN:P in Town Cove, we did collect considerable data of this

sort during the investigation. As seen in Tables 10-13, there was a clear trend for the PC:PN ratio of the filtered particulate matter to be in the range 4-7 (by weight) and for the ΣN:P ratio of the dissolved nutrients to be <5 (by atoms).

2. Nutrient Enrichment Bioassays. A standard protocol adapted by the EPA for measuring the eutrophication potential of a water body is to artificially enrich water samples with inorganic nitrogen and/or phosphorus and to incubate the samples for a period of time. Increases in algal biomass over time in particular samples will reflect which nutrient (if any) limits algal growth.

In conjunction with our primary productivity studies, we performed five nutrient enrichments bioassays over the course of the study. In the first three experiments two samples from both the cove (Station 3) and the cove inlet (Station 9) were enriched with nutrients: 16 ug atoms/liter of NH_4^+ in one sample and 5 ug atoms/liter of PO_4^{-3} in the other. Only NH_4^+ enrichment was used in the last two studies. The bioassays were performed exactly as were the primary productivity incubations. As seen in Table 15, the ratios E_N (the ratio of productivity rates with and without NH_4^+ enrichment) and E_P (the ratio of productivity rates with and without PO_4^{-3} enrichment) never varied appreciably from 1.0 in both the inlet and cove samples, indicating a lack of either nitrogen or phosphorus limitation on the dates the assays were performed.

3. Dark Enrichment Bioassays. Another type of enrichment bioassay is based on the fact that when algae are nitrogen-limited they will fix CO_2 in substantial quantities in the dark for short periods when pulsed with NH_4^+. The enhancement ratio, which is the ratio of dark CO_2 fixation with and without

Table 15. Results of nutrient enrichment bioassays, in Town Cove, Orleans.

Date	Temp. (°C)	Incident Irradiance (W/m^2)	(%)	P (ugC/l/hr) Control	$+ NH_4^+$	$+ PO_4^{-3}$	E_N*	E_P**
Oct. 20, 1982	12	3882	30	24.6	27.6	26.1	1.12	1.06
Oct. 21, 1982	13	2815	30	31.2	30.9	30.0	0.99	0.9[illegible]
Dec. 7, 1982	11–12	2075	30	95.0	99.5	98.5	1.05	1.04
May 18, 1983	10.5–11.5	7680	30	49.7	51.1	–	1.03	–
Aug. 5, 1983	23–24	6475	30	29.0	35	–	1.21	–

*P ($+ NH_4^+$): P (Control)
**P ($+ PO_4^{-3}$): P (Control)

NH_4^+ enrichment, is thus another indicator of the degree of nitrogen limitation in a water body-values of the enrichment ratio over 2 indicate nitrogen limitation. We performed six of these bioassays in darkened assay chambers and never found the enrichment ratio to exceed 1.7 (Table 16), thereby providing another strong indication that algal productivity in Town Cove was not limited by nitrogen during the study period.

4. Nitrogen Uptake Experiments. We performed two experiments during the Fall, 1982 to determine the form of nitrogen being utilized by algae in Town Cove. These experiments consisted of a series of incubations similar to the primary productivity studies, but in this case we enriched the samples with ^{15}N-labelled NH_4^+, urea, NO_3^-, or NO_2^-. Rates of nitrogen uptake were then calculated for the different types of nitrogen by measuring the amount of ^{15}N in the filtered samples over time compared to ^{14}N. These experiments were performed by our colleague, Dr. Patricia M. Glibert, who is an expert on the use of ^{15}N in nitrogen uptake studies with algae.

Two important indicators of the degree and form of nitrogen limitation can be derived from ^{15}N uptake experiments. The first is a comparison of the rates of nitrogen uptake of samples enriched with "trace" and saturating concentrations of nitrogen. The "trace" concentration of 0.06 ug atoms/liter of ^{15}N-lableled substrate that we added is supposed to serve as true tracer. However, often ambient concentrations of the different forms of nitrogen are at, or below, this level so that the added nitrogen represents a significant increase in the ambient nitrogen concentration. The saturating addition of 16 ug atoms/liter of nitrogen ensures enrichment to a level that exceeds the uptake capacity of the algal population. Thus if the ratio of V_{sat} (the

Table 16. Results of Dark NH_4^+ Enrichment Bioassays, Town Cove, Orleans.

Date	Temp. (°C)	^{14}C Accumulation* (ug C/l) Control	+ NH_4	Enhancement Ratio
Oct. 20, 1982	12	8.5	3.1	0.36
Oct. 21, 1982	13	9.9	9.4	0.95
Dec. 7, 1982	11-12	3.0	3.2	1.07
Feb. 16, 1983	1	0.3	0.5	1.67
May 18, 1983	10.5-11.5	1.2	1.8	1.50
Aug. 5, 1983	23-24	2.1	1.8	0.86

*Based on 1-2 hr incubations.

specific N uptake rate during exposure to saturating nitrogen) to V_{trace} (the specific N uptake rate during exposure to "trace" nitrogen) is significantly greater than 1.0 then nitrogen limitation would be presumed. A value close to 1.0 (<3-4) would reflect non-nitrogen limitation because it indicates that nitrogen uptake rates of the algal population are close to, or at, maximum levels.

Summarized in Tables 17 and 18 are the nitrogen uptake data for experiments conducted on September 24, 1982 and October 20, 1982. These studies were designed to compare uptake rates between Stations 9 and 3. Specific uptake rate of NH_4^+, urea, and NO_3^- during October at Station 3 after 2 hrs incubation exceeded those during September at this station by factors of \40, >100, and \7, repectively, even though ambient nutrient concentrations during this period increased by factors of only 6, 30, and 3, respectively (Table 17). Specific uptake rates of NO_2^- were very low during both months and the differences between months was not significant. Similar trends were found for the incubations from Station 9, although urea uptake was more pronounced during September at this location.

There was no evidence, based on the ratios of saturating to trace uptake rates, that nitrogen limitation existed in the algal populations entering Town Cove on both dates. Uptake ratios of all nitrogen sources generally were, at the extreme, not much above 4.0 during the course of the incubations (Table 18).

In addition, ΣN concentrations at the cove station during both study periods exceeded those nitrogen levels that would typically denote nitrogen sufficiency in algal populations.

Table 17. Nitrogen uptake data for "trace" enrichments experiments on samples from inlet (Station 9) and along shore (Station 3) of Town Cove, Orleans during Fall, 1982.

Date	Station	ΣN (ug at/l)	Incubation Duration (h)	Specific Nitrogen Uptake Rate (hr^{-1}) V NH_4^+	V Urea	V NO_3^-	V NO_2^-
Sept. 24, 1982	3	3.83	0.08	0.207	0.033	0.018	0.008
			0.5	0.034	0.004	0.005	0.001
			1.0	0.030	0.001	0.002	0.001
			2.0	0.025	0.003	0.001	0.001
	9	1.53	0.08	0.045	0.619	0.041	0.010
			0.5	0.012	0.177	0.055	0.009
			1.0	0.021	0.022	0.002	0.002
			2.0	0.009	0.023	0.001	0.001
Oct. 20, 1982	3	30.28	0.08	1.60	1.17	0.045	0.008
			0.5	1.44	0.71	0.049	0.011
			1.0	1.22	0.93	0.015	0.010
			2.0	0.93	0.40	0.006	0.001
	9	0.69	0.08	0.17	0.129	N.D.	N.D.
			0.5	0.14	0.008	0.036	0.012
			1.0	N.D.	0.017	0.025	0.001
			2.0	0.13	0.026	0.019	0.003

Table 18. Analysis of V_{sat}/V_{trace} for all dissolved nitrogen sources in samples from inlet (Station 9) of Town Cove, Orleans during Fall, 1982.

Date	Incubation Duration (h)	$\frac{V_s}{V_t}$	$\frac{V_s}{V_t}$	$\frac{V_s}{V_t}$	$\frac{V_s}{V_t}$
Sept. 24, 1982	0.08	4.53	1.0	1.0	2.23
	0.5	3.43	1.0	1.0	1.27
	1.0	2.00	1.23	4.55	3.3
	2.0	6.38	1.30	4.2	7.2
Oct. 20, 1982	0.08	2.55	2.69	N.D.	N.D.
	0.5	1.0	17.4	1.0	1.54
	1.0	N.D.	2.44	1.0	2.88
	2.0	1.0	2.21	1.0	4.60

The second index that can be derived from nitrogen uptake data is the relative preference algae have for a particular nitrogen source in relation to the availability of that form of nitrogen relative to ΣN. The index, known as RPI (the relative preference index), is simply the ratio of the fractional uptake rate for one nitrogen source (in relation to the total uptake rate) to the fractional concentration of that nitrogen source (in relation to ΣN). Values of RPI> 1.0 represent preferred uptake of that nitrogen source in relationship to its availabilty, whereas values of 1.0 indicate uptake in proportion to availability. As seen in Fig. 15, relative uptake of each nitrogen source (as based on RPI values not much different than 1.0) was in approximate proportion to relative availability, thereby indicating that total nitrogen uptake was in proportion to the availability of ΣN.

The pooled results from the four different indices we used to test for nitrogen limitation provide for an overwhelming case against any form of nitrogen or phosphorus limitation of algal growth in Town Cove.

E. Tidal Exchange Nutrient and Biomass Mass Balance

The major inputs of nitrogen anticipated in the Town Cove Basin, as seen in Fig. 16, are groundwater (N_G), surface runoff (N_R), tidal input (N_F), and bird and fowl fecal discharges (N_B). Over the course of a complete tidal exchange the sum of these inputs should be balanced by the sum of nitrogen leaving the cove through tidal output (N_E), and denitrification processes (N_D), together with storage processes within the cove itself such as deposition in the sediments and accumulation by benthic organisms (N_S) and incorporation into rooted plant material and seaweeds (N_P). Quantitatively, a nitrogen mass

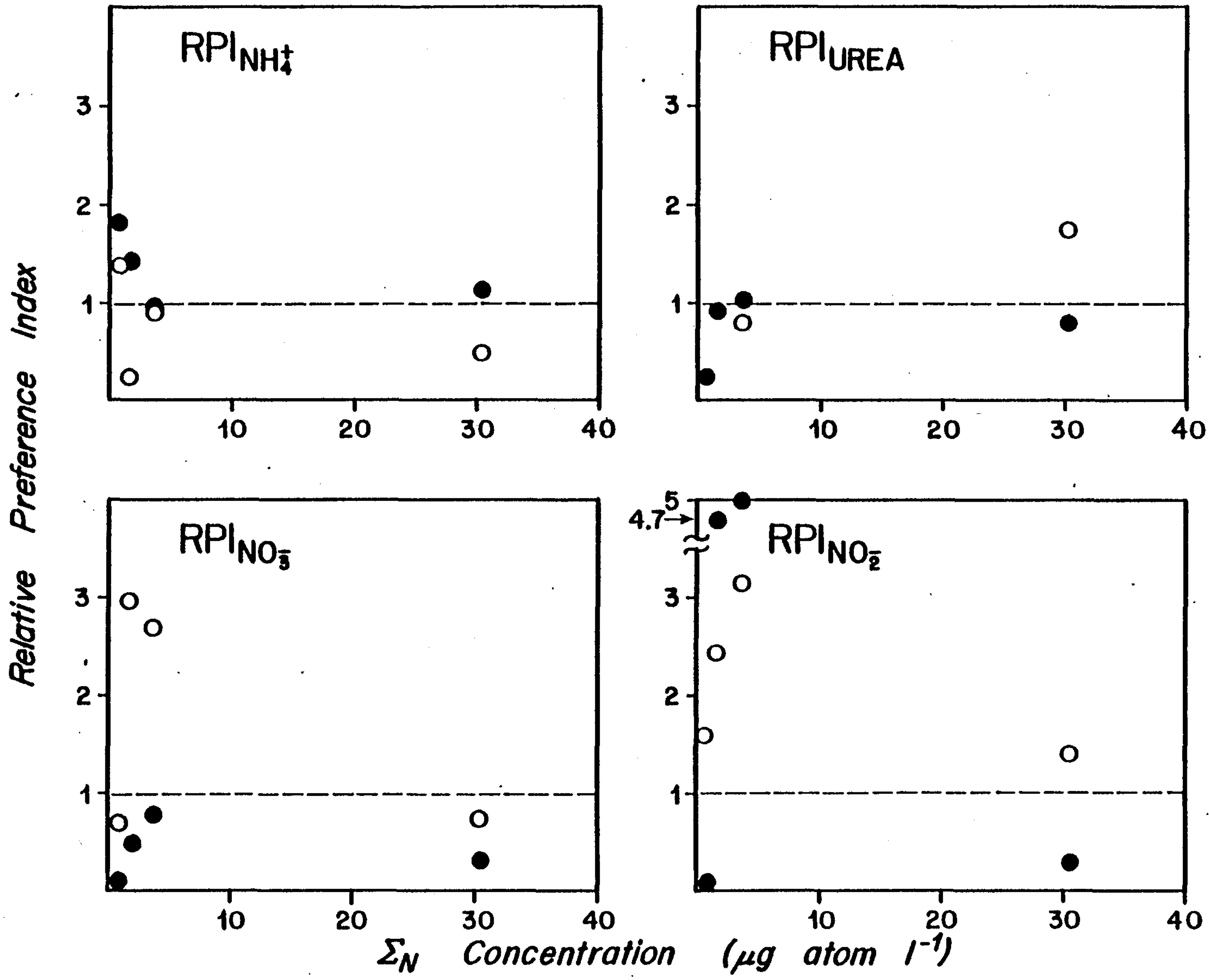
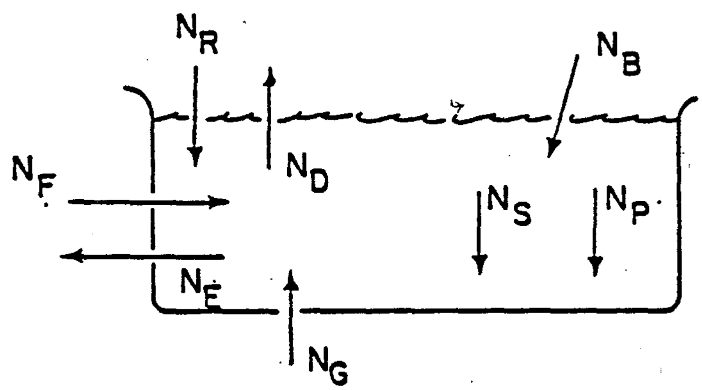


Figure 15. Relative preference index (RPI) as a function of total dissolved nitrogen (ΣN) for (A) NH_4^+, (B) urea, (C) NO_3^-, (D) NO_2^- for collected samples obtained at both inlet (Station 9) and along shore (Station 3) in Town Cove, Orleans on September 24 and October 20, 1982. ○ = 30 minute incubations; ● =120 minute incubations.

NITROGEN MASS BALANCE
TOWN COVE



N_R = ΣN IN - RUNOFF
N_B = ΣN IN - BIRDWASTES
N_G = ΣN IN - GROUND WATER
N_F = ΣN IN - FLOOD TIDE
N_E = ΣN OUT - EBB TIDE
N_S = ΣN- STORED in SEDIMENTS & SHELLFISH
N_P = ΣN STORED in PLANTS
N_B = N_2 LOST by DENITRIFICATION

Figure 16. Nitrogen mass balance, Town Cove Cod, Massachusetts.

balance for one tidal exchange in Town Cove is as follows:

$$\begin{array}{ccccc} \text{IN} & & \text{OUT} & & \text{STORED} \\ [N_F + N_G + N_R + N_B] & = & [N_E + N_D] & + & [N_S + N_P] \end{array}$$

In trying to gauge the impact of groundwater nitrogen (N_G) on eutrophication in Town Cove, it is critical that the magitude of this input term relative to the other flux terms in the above equation, particularly the tidal exchange terms N_F and N_E, be established.

During the course of the study we performed three tidal mass balance experiments, one on October 20-21, 1982, another on April 26-27, 1983, and the last on June 29-30, 1983. The protocols for these experiments involved taking water samples on an hourly basis over 24 hr at the Mead Station. All tidal water entering and leaving the cove passes through the narrow channel at this station (See Fig. 12). A suite of nutrient and biological analyses were subsequently performed on all samples. These data, together with tidal volume discharge data obtained for these study periods from Dr. David Aubrey, a co-investigator on the project (See Fig 39), were then used to calculate the mass flux over the course of two complete tidal exchanges in each experiment for all the chemical and biological constituents we measured in the water samples. The parameters measured included NH_4^+, urea, NO_3^- + NO_2^-, PC, PN, PO_4^{-3}, and chlorophyll a.

Summarized in Figs. 17-19 are plots of mass flux in and out of Town Cove during the three experiments for three major parameters: total dissolved nitrogen ΣN (NH_4^+ + urea + NO_3^- + NO_2^-), total nitrogen TN (ΣN + PN), and dissolved inorganic phosphorus. Total mass balances of all measured constituents are

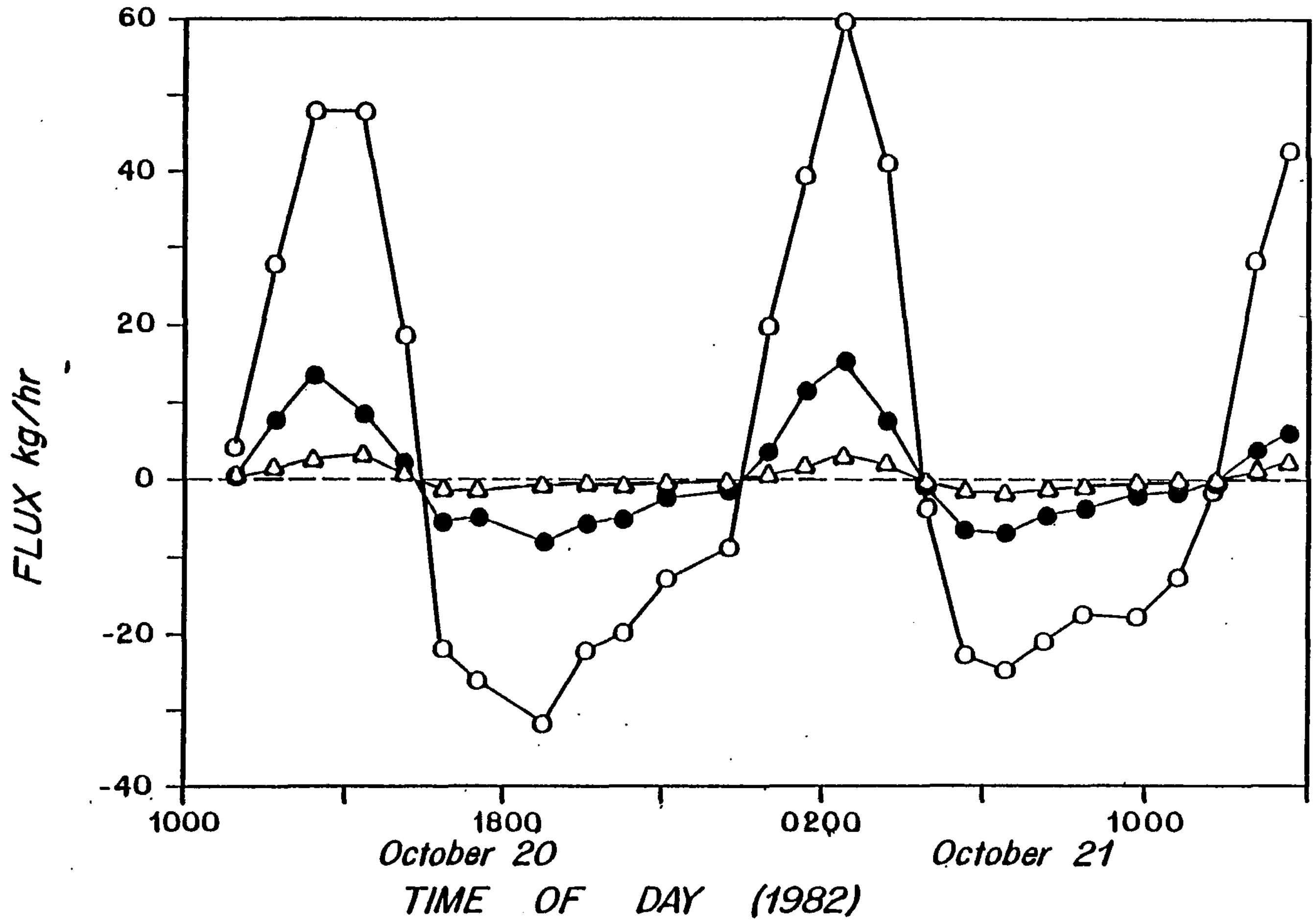


Figure 17. Calculated tidal exchange of nitrogen and phosphorus species at Mead's Station (see Fig. 12) over two flood and ebb tidal cycles. Town Cove, Cape Cod, MA. October 20-21, 1982. ○ = Total Nitrogen △= Phosphorus ●= Dissolved Nitrogen

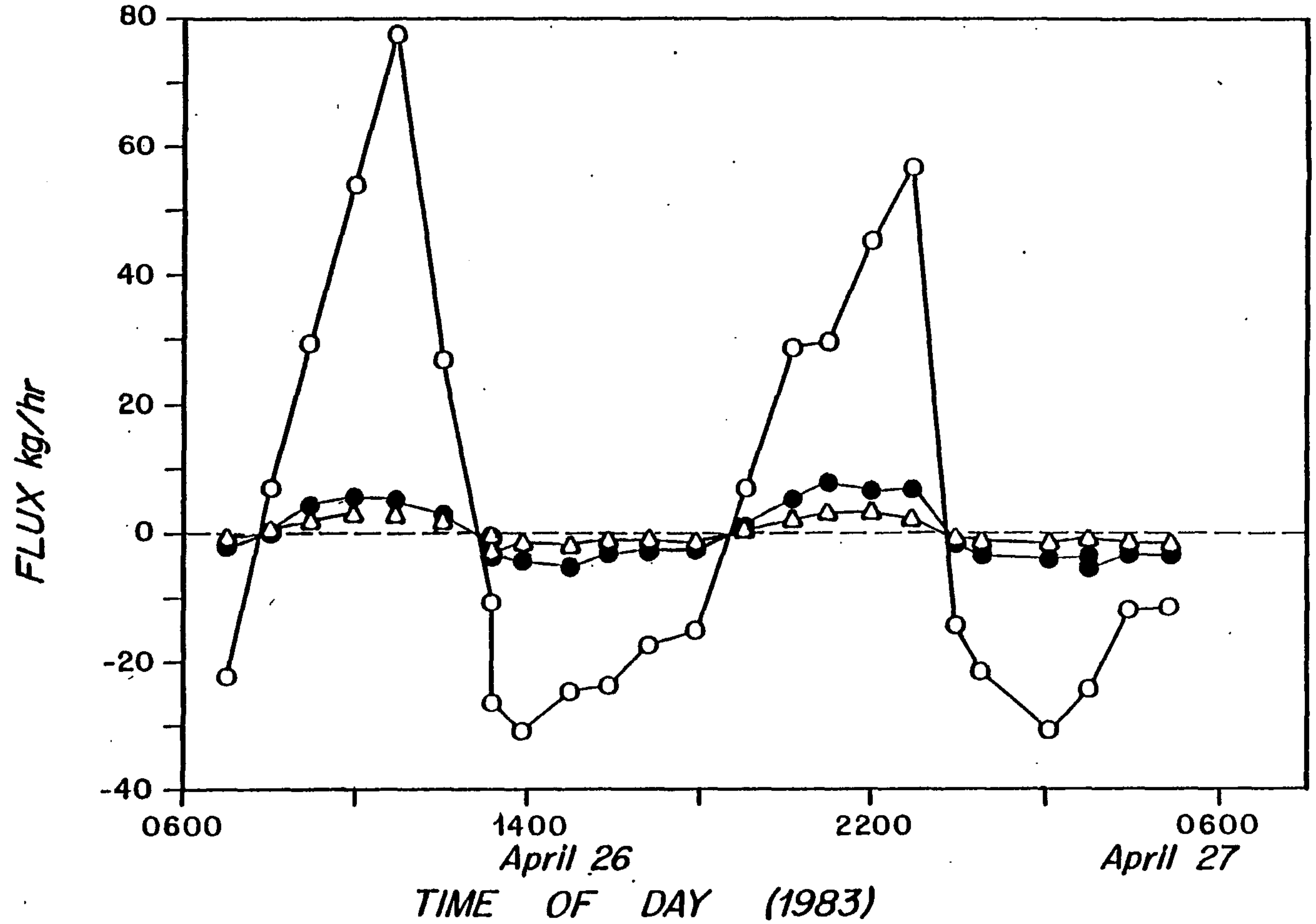


Figure 18. Calculated tidal exchange of nitrogen and phosphorus species at Mead's Station (see Fig. 12) over two flood and ebb tidal cycles. Town Cove, Cape Cod, Mass. April 26-27, 1983. o =Total Nitrogen ● = Dissolved Nitrogen Δ = Phosphorus

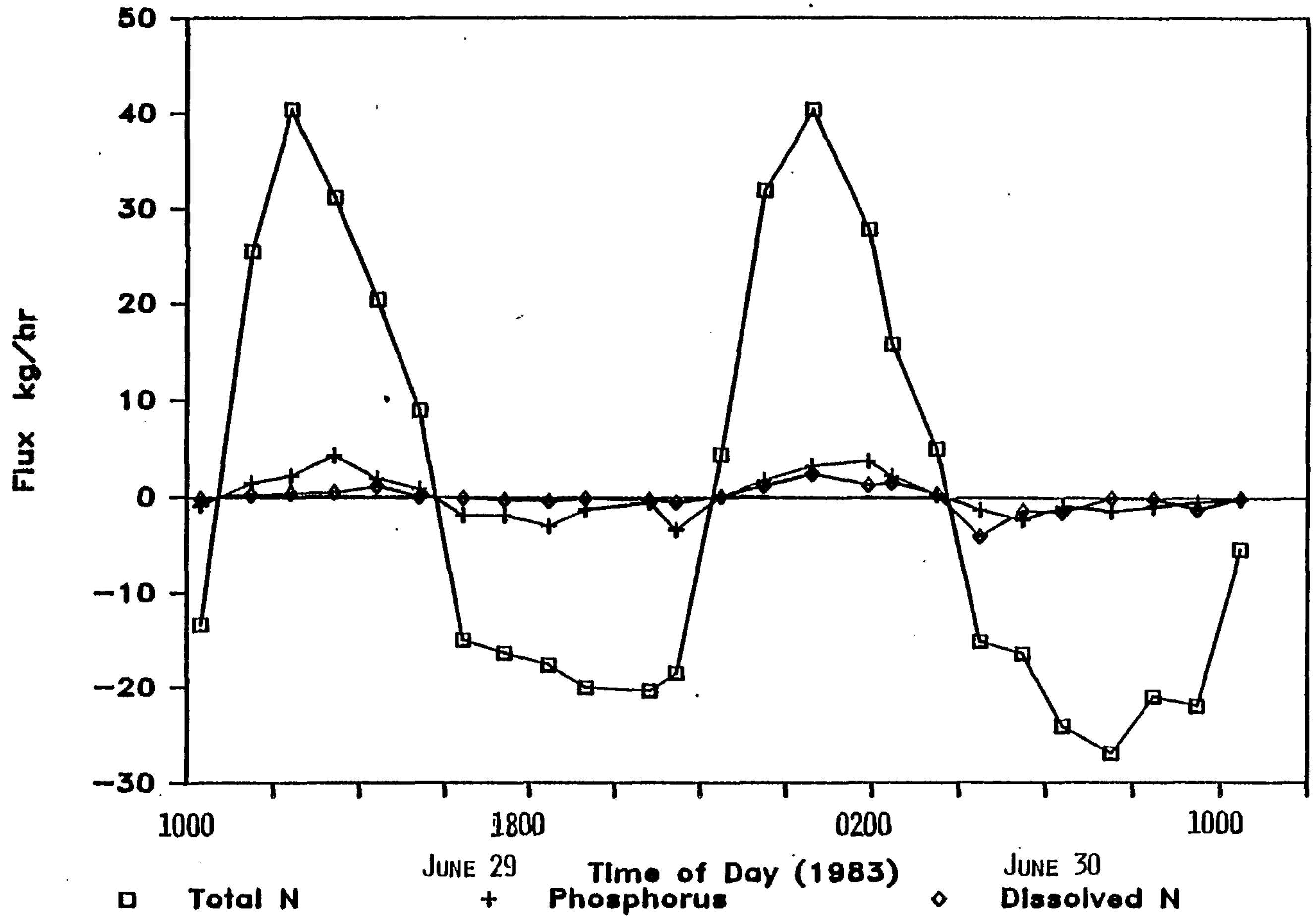


Figure 19. Calculated tidal exchange of nitrogen and phosphorus species at Mead's Station (see Fig. 1) over two flood and ebb tidal cycles. Town Cove, Cape Cod, Mass. June 29-30, 1983.

tabulated in Tables 19-21. A common feature of the three studies was that there was a substantial net influx of TN into Town Cove and that the bulk of this nitrogen was in the particulate form (PN), ranging from 67% on October 20-21, 1982 to 97% of TN on April 26-27. In addition, there was a net but relatively small influx of ΣN during the first two experiments. In contrast, there was a small outflux of both TN and ΣN during the June 29-30, 1983 experiment.

There also was a small net influx of inorganic phosphorus on all occasions and either no exchange (October 20-21, 1982) or an influx of chlorophyll a (April 26-27 and June 29-30, 1983). The quantities of imported chlorophyll, although of the same magnitude by weight as ΣN, actually represent very significant quantities of algal biomass because chlorophyll constitutes a very small fraction of algal biomass relative to carbon and nitrogen.

The net influx of particulate material, represented by PC, was about twice as great during the April, 1983 experiment than during the October, 1982 study. However, there was a substantial export of PC during the June, 1983 experiment (Table 21) which was not balanced by a large export of PN.

There were interesting (but puzzling) changes in the PC:PN ratio of the particulate material exchanging at the Mead Station (Fig. 20). The ratios varied from low values ($\sim$5-6) to highs of 10-11 in irregular patterns over the three experiments. Increases in PC:PN during day, followed by decreases at night would be the expected pattern in a non-flowing system. However, tidal exchanges of particulate material of unknown origin from outside of the cove would be expected to complicate tremendously any biologically-controlled change in the PC:PN ratio of algal biomass. Yet, during October 20, 1982 we observed the expected daytime increase in PC:PN during the flood tide, followed by an

Table 19. Nitrogen mass balance for tidal exchange in Town Cove, Orleans, October 20-21, 1982. Samples collected at Mead Station.

	IN (kg)			OUT (kg)			Diff.	IN-OUT/IN
Constituent	AM	PM	Total	AM	PM	Total	kg	*100
NH_4^-	15.1	20.7	35.6	9.6	14.7	24.3	11.4	32
Urea	11.3	10.2	21.5	15.6	6.8	22.4	-0.9	-4
$NO_3^-+NO_2^-$	9.4	6.7	16.1	7.8	4.1	11.9	4.2	26
ΣN	35.8	37.6	73.2	33	25.6	58.6	14.6	20
PN	113.4	121.6	235	110	95.3	205.3	29.7	13
TN	149.2	159.2	308.2	143	120.9	263.9	44.3	14
PO_4^{-3}	8.6	7.6	16.2	5.4	6.6	12	4.2	26
Chl *a*	2.3	2	4.3	2.1	2.3	4.4	-0.1	-2
PC	888	768	1656	788	574	1362	294	18
Water mass (m3)	1336700	1198400	2535100	1240400	1104900	2345300	189800	7.48

Table 20. Nitrogen mass balance for tidal exchange in Town Cove, Orleans, April 26-27, 1983. Samples collected at Mead Station.

Constituent	IN (kg)			OUT (kg)			Diff. IN-OUT/IN	
	AM	PM	Total	PM	AM	TOTAL	kg	*100
NH_4^+	4.15	6.39	10.55	4.85	5.74	10.59	-0.04	-0.40
Urea	6.71	9.41	16.12	7.03	7.88	14.91	1.21	7.49
$NO_3^-+NO_2^-$	8.80	13.35	22.15	9.94	10.84	20.78	1.36	6.16
ΣN	19.66	29.15	48.81	21.81	24.47	46.28	2.53	5.18
PN	176.20	138.81	315.01	126.90	113.23	240.13	74.88	23.77
TN	195.86	167.96	363.82	148.71	137.70	286.41	77.41	21.28
PO_4^{-3}	9.97	11.46	21.43	10.72	8.27	18.98	2.45	11.42
Chl *a*	2.18	3.19	5.36	2.05	1.96	4.01	1.36	25.27
PC	1171.93	1184.82	2356.75	969.75	938.10	1907.85	448.90	19.05
Water mass (m3)	1530946	1859960	3390906	1859960	1678860	3538820	-147914	-4.36

Table 21. Nitrogen Mass Balance for Tidal Exchange in Town Cove, Orleans. June 29-30 1983. Samples collected at Mead Station.

	IN (kg)			OUT (kg)			Diff.	IN-OUT/IN
Constituent	AM	PM	TOTAL	PM	AM	TOTAL	kg	*100
NH_4^-	0.32	1.95	2.27	0.43	0.87	1.30	0.97	42.57
$NO_3^-+NO_2^-$	0.48	0.97	1.44	0.49	0.85	1.34	0.10	7.17
Urea	1.63	4.05	5.68	0.67	7.37	8.04	-2.36	-41.58
ΣN	2.43	6.96	9.40	1.59	9.09	10.69	-1.29	-13.75
PN	124.02	118.51	242.53	106.33	148.94	255.27	-2.94*	-1.21
TN	126.45	125.48	251.93	107.92	158.04	265.96	-3.93*	-1.56
PO_4^{-3}	10.88	11.54	22.41	12.11	9.49	21.60	0.82	3.64
Chl a	2.87	1.81	4.67	1.40	2.03	3.43	1.24	26.60
PC	1033.57	888.76	1922.33	1050.99	1334.49	2385.48	-370.85*	-19.29
Water mass (m3)	1125841	1301515	2427356	-1062166	-1456163	-2518329	-90973	-3.7478

* corrected for net tidal outflow over the sampling period

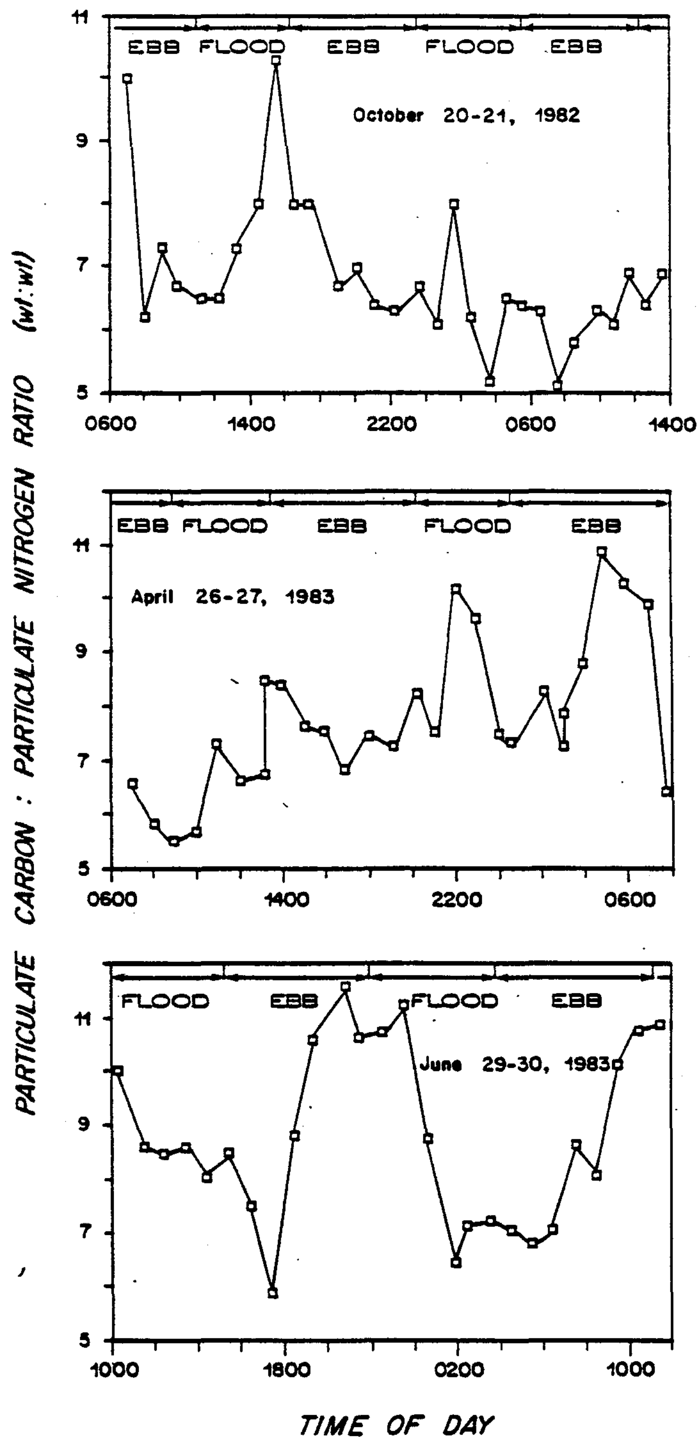


Figure 20. Summary of PC:PN ratio data collected at Mead Station during 24-hr. studies on October 20-21, 1982; April 26-27, 1983; and June 29-30, 1983.

evening decrease that coincided with the ebb tide. These results suggest that some fraction of imported particulate material during the day of the first two study periods was actively growing algal biomass from the connecting inland waters (Nauset Harbor and Salt Pond Bay) and that daytime photosynthetic uptake of carbon exceeded nitrogen uptake. Photosynthesis ceased during the evening, but nitrogen uptake continued at a high rate as biomass was being exported. A similar day-night pattern of increase in PC:PN followed by a decrease occurred on April 29 even though the phasing of ebb and flood tides was quite different than on October 20, 1982. The patterns of diurnal change in PC:PN during the June, 1983 study were, however, somewhat different - daytime decreases in PC:PN during the flood tide, followed by early evening increases during the ebb tide and then the characteristic decrease at night, but this time during the flood tide.

The above results are not easy to interpret, but we suspect that the pattern of daytime increase in PC:PN followed by a decrease during the night, irrespective of the tidal cycle, is indicative of active algal growth in the entire inland water system of which Town Cove is a part. This conclusion is supported by the facts that there generally was a small net influx of chlorophyll a into Town Cove and relatively high algal productivity at Station 9.

F. Conclusions

Two important conclusions immerge from our part of the study. First, on the basis of a variety of biological and chemical indices, we are confident in concluding that algal productivity in Town Cove is not nitrogen limited. It is difficult to catagorically state that increased additions of anthropogenic nitrogen will not lead to increased algal biomass, mainly because of the problem of separating growth rate from yield responses to nitrogen additions. Clearly, nitrogen addition to Town Cove will have no impact on algal growth rates because these rates appear to be close to maximal levels.

Net increases in algal biomass, as we have pointed out, are not necessarily linked to high growth rates. However, our second conclusion, namely that Town Cove is a sink for nitrogen over a large portion of the year, can shed some light on the question of biomass buildup in Town Cove. Based on our mass balance experiments, it appears that virtually all anthropogenic groundwater NO_3^- entering Town Cove is being converted biologically to particulate nitrogen. Efflux of NO_3^- and NO_2^- does not occur and only marginal quantities of NH_4^+ are exported at times. Thus the build up of nitrogen in Town Cove must equal virtually all PN derived from anthropogenic groundwater inputs (N_G), as well as large quantities of PN entering during the flood tide. The fate of this PN is unknown, but we suspect that settling of particulates and accumulation in the sediments at the center of the cove generally is enhanced greatly during the ebb tide because of the unique geometry of Town Cove (a narrow shallow channel entrance and a long and narrow basin that is relatively deep in the center) together with an asymmetric tidal cycle (slow ebb tide followed by a fast flood tide - see section on Physical Modelling).

It is difficult to gauge the impact of this net accumulation of particulate nitrogen on eutrophication in Town Cove. We do suspect, however, that natural eutrophication of Town Cove, independent of any human influence, is occurring at a steady, if not enhanced rate. For example, the total daily input of nitrogen to Town Cove from tidal exchange alone varied from 44 kg in the

October, 1982 study to about 80 kg in the April, 1983 study. If we assume that the average total nitrogen load in domestic wastewater is about 20 gm/capita/day (a typical and well-documented value for U.S. domestic wastewater), then the population equivalent for the nitrogen entering Town Cove from tidal exchange on these dates is between 2000 and 4000 people. In other words, the amount of nitrogen that could be deposited daily in Town Cove by way of tidal exchange alone is equivalent to a direct daily discharge of wasterwater-borne nitrogen into the cove from up to 4000 people.

Sediment-Water Interactions and Exchanges

Anne E. Giblin, Department of Biology

A. Loss of Groundwater Nitrogen Through Denitrification

Certain bacteria are capable of reducing nitrate (NO_3-) and nitrite NO_2-) to nitrous oxide (N_2O) or nitrogen gas (N_2) by a process known as denitrification. Since N_2O and N_2 cannot be directly used by plants, denitrification can effectively remove nitrogen as a nutrient from an ecosystem. My objective here is to assess the importance of denitrification in Town Cove where nitrate-containing groundwater passes through estuarine sediments. To study this, we made a large number of measurements of nitrate and salinity in conjunction with our other measurements on groundwater. Sampling was concentrated in areas where groundwater movement was thought to be large or where nitrate concentrations were high.

When groundwater (which contains little or no salt) mixes with sea water the salinity increases with the proportion of sea water, so salinity can be used as a conservative tracer of mixing. Nitrate levels are generally much lower in sea water than in groundwater, so where they mix the groundwater nitrate concentration is expected to drop. If no biological process adds or removes nitrate from the solution the magnitude of the drop will be proportional to the degree of mixing. In our porewater measurements we used salinity as a conservative tracer of mixing to determine if nitrate was being added or lost. Measurements were conducted by taking samples of porewater from several depths below the sediment water interface. This was normally done at 3-5 locations along transects extending out from the shore. The water was usually analyzed for ammonia and phosphate in addition to nitrate, nitrite and salinity.

Over the course of the study 195 measurements were made. In two transects groundwater samples containing quite high levels of nitrate occured 15-20 cm below the sediment surface close to shore (Figs 21, 22). These two stations showed a trend of increasing nitrate concentration and decreasing salinity with greater depth in the sediment. The station near BW 5 only show two samples in which the nitrate concentration fell below the conservative mixing line. Station BW 3 had several samples which fell below the mixing line. In both cases the points which fell below the mixing line were farther out from shore.

More typical results from the transects are shown in Figs. 23 and 24. In these profiles there is no tendency for nitrate concentration to decrease with salinity. Station 6 (November 19) is representative and shows that both the absolute concentration of nitrate and the amount of nitrate corrected for dilution increases with increasing salinity. A partial explanation for this can be seen in the ammonia profiles (Figs. 25 and 26). Along with the increase in nitrate, there is a decrease in ammonia suggesting oxidation of ammonia to nitrate. Unlike denitrification, this process of nitrification does not involve the conversion of nitrogen to gases that can be lost from the system. Since both ammonia and nitrate can be used by plants, this change has no effect on the nitrogen budget. Our measurements suggest another cause of the increase in nitrate concenrations near the surface could be the release of nitrogen during the decay of organic matter (remineralization). When corrected for dilution, Station 4 (September 29, 1983) shows an increase in the total nitrogen present in the sediments and an increase in phosphorous which indicates nutrients are

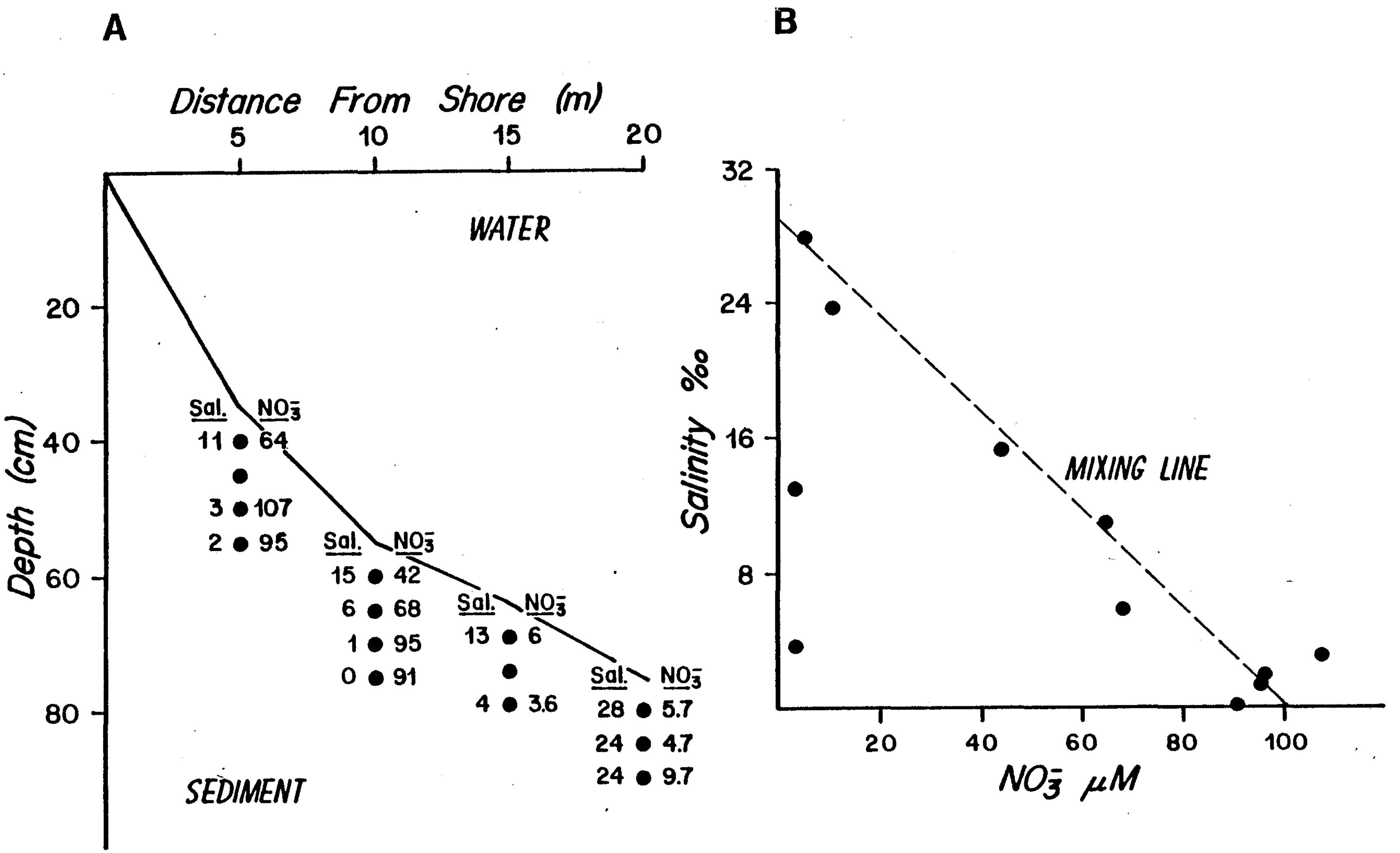


Figure 21. A) Nitrate concentrations (uM/l) and salinities (o/oo) in porewater from cores taken along a transect offshore from Beach Well 5, Town Cove, Mass. Dots give the approximate depth of the samples (5 cm intervals) and their distance offshore; and B) salinity/nitrate relationship in porewater and the theoretical relationship (dotted line) if dilution alone is responsible for observed concentrations.

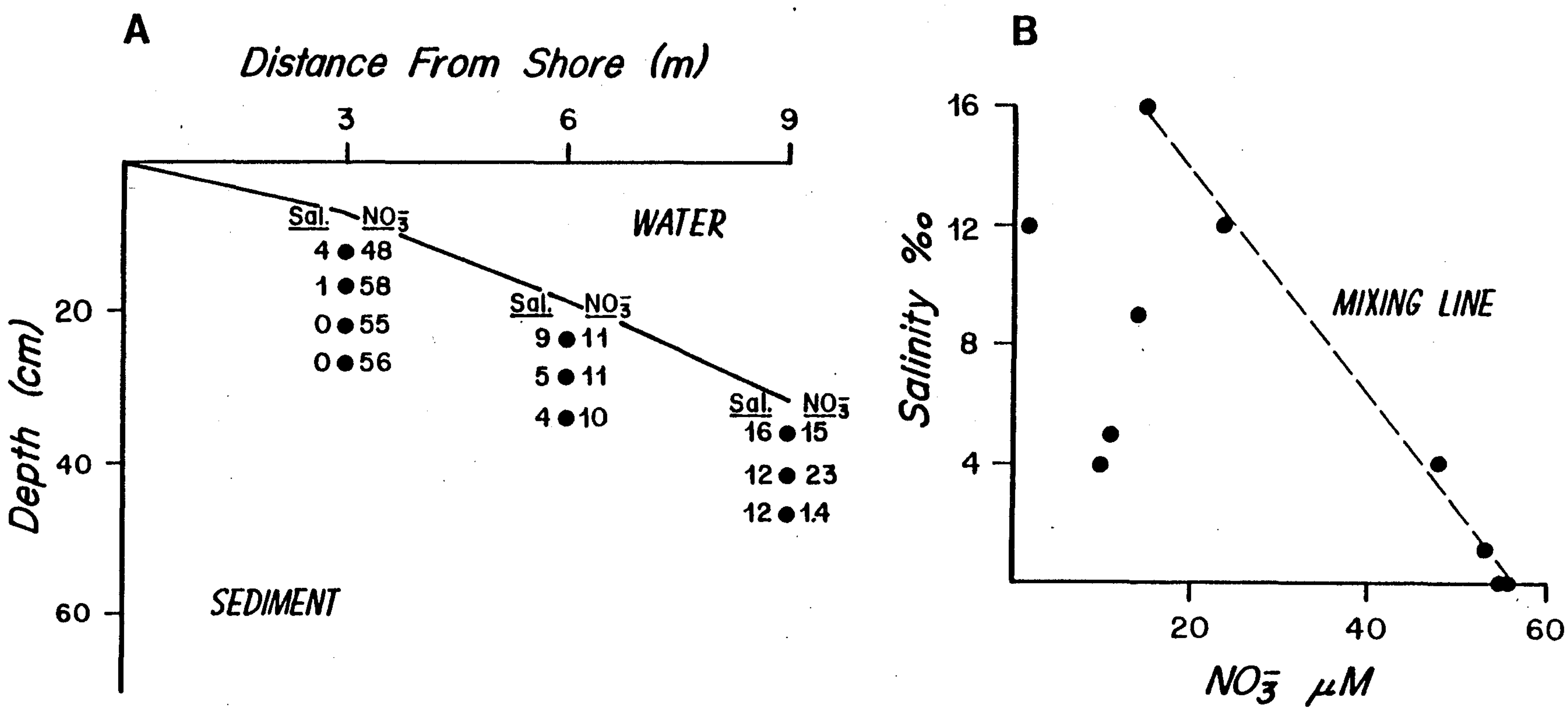


Figure 22. A) Nitrate concentrations (uM/l) and salinities (o/oo) in porewater from cores taken along a transect offshore from Beach Well 3, Town Cove, Mass. Dots give the approximate depth of the samples (5 cm intervals) and their distance offshore; and B) salinity/nitrate relationship in porewater and the theoretical relationship (dotted line) if dilution alone is responsible for observed concentrations.

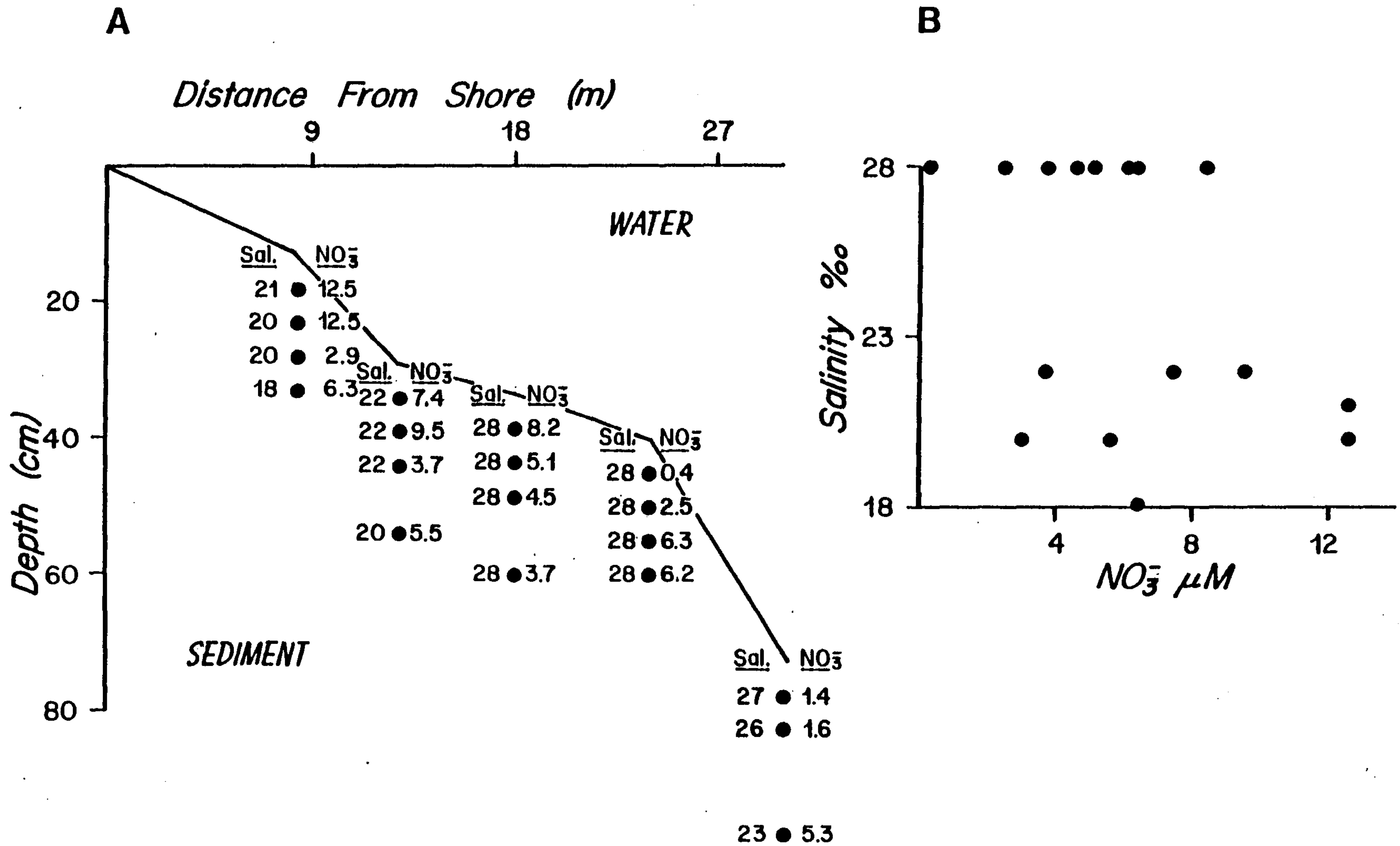


Figure 23. A) Nitrate concentrations (uM/l) and salinities (o/oo) in porewater from cores taken along a transect offshore from biological sampling station 6, Town Cove, Mass. Dots give the approximate depth of the samples (5 cm intervals) and their distance offshore; and B) nitrate/salinity relationship.

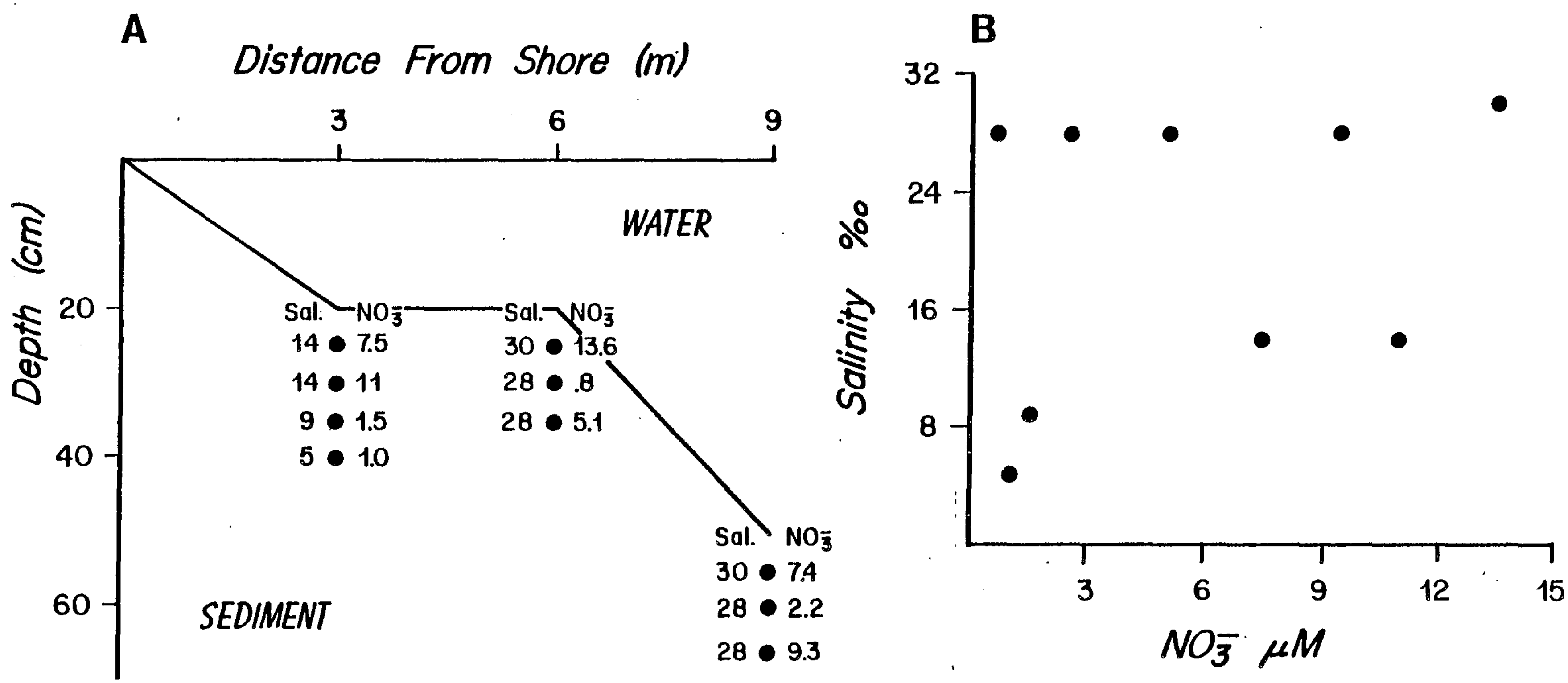


Figure 24. A) Nitrate concentrations (uM/l) and salinities (o/oo) in porewater from cores taken along a transect offshore from biological sampling station 14, Town Cove, Mass. Dots give the approximate depth of the samples (5 cm intervals) and their distance offshore; and B) nitrate/salinity relationship.

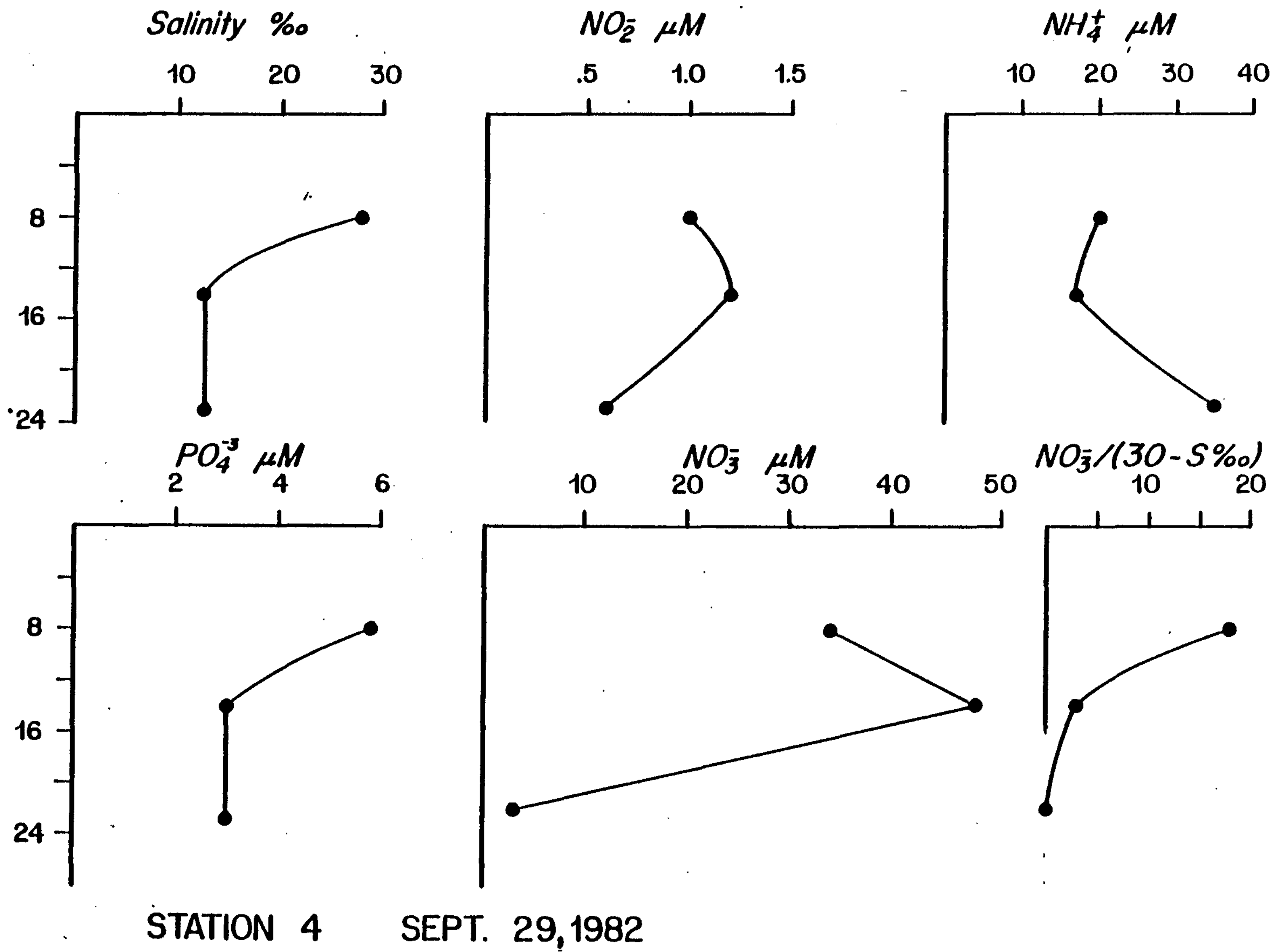
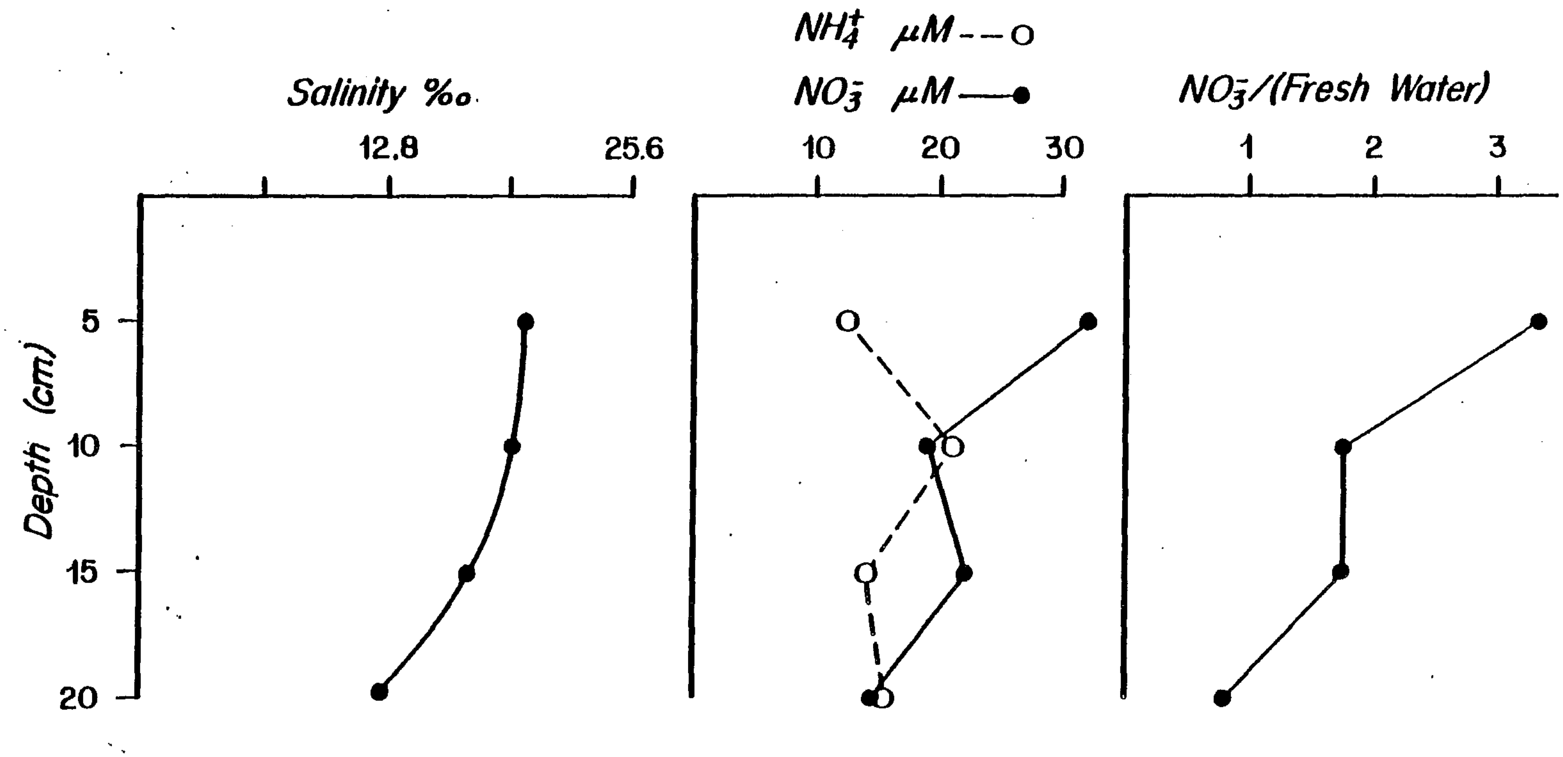


Figure 25. Profiles of salinity (o/oo), ammonia, and nitrate (uM/l) in sediment porewater from a core taken at Station 4, Town Cove, Mass. The ratio of nitrate/freshwater is defined as the nitrate concentration divided by (30 minus measured salinity). See text for explanation.



STATION 6 NOV. 19, 1982

Figure 26. Profiles of salinity (o/oo), ammonia, and nitrate (uM/l) in sediment porewater from a core taken at Station 6, Town Cove, Mass. The ratio of nitrate/freshwater is defined as the nitrate concentration divided by (30 minus measured salinity). See text for explanation.

being remineralized in the sediments. This addition represents the recycling of nutrients already present in the cove and do not represent a source of new nitrogen.

From these observations we see no evidence for widespread denitrification in the sandy areas around the perimeter of the cove where groundwater infiltration is high. The ratio of nitrate to salinity in these areas is affected by remineralization and nitrification. Increases in nitrate levels near the surface of the sediments indicate that conditions are not favorable for denitrification. Changes in nitrate concentrations by nitrification and remineralization are only changes in form and do not affect our nitrogen budget. By measuring the groundwater flow and the nitrogen concentration in the groundwater, the method used in this study and described earlier in this report, we believe we are accurately determining the amount of nitrogen entering the cove.

We have indirect evidence that denitrification is occurring in the central areas of Town Cove. Porewater profiles show that the sediments there are quite reducing below 0.5 cm and contain high levels of sulfide (Fig. 27). These conditions favor denitrification if nitrate is present, as is indicated in Fig. 27. It is possible that nitrate is produced from oxidation of ammonia near the sediment surface. The profiles also show that nitrate is diffusing downward in the sediment, where it could be consumed by denitrification. Our profile of nitrogen is quite similar to published profiles (e.g., Vanderborgt et al. 1977; see Fig. 28). From these observations we believe the deeper waters and sediments of Town Cove could be an ideal environment for denitrification. Nixon (1981) has estimated that 5-25% of nitrogen reaching the sediments is lost by this process. We feel it could be a large term in the nitrogen budget for Town Cove.

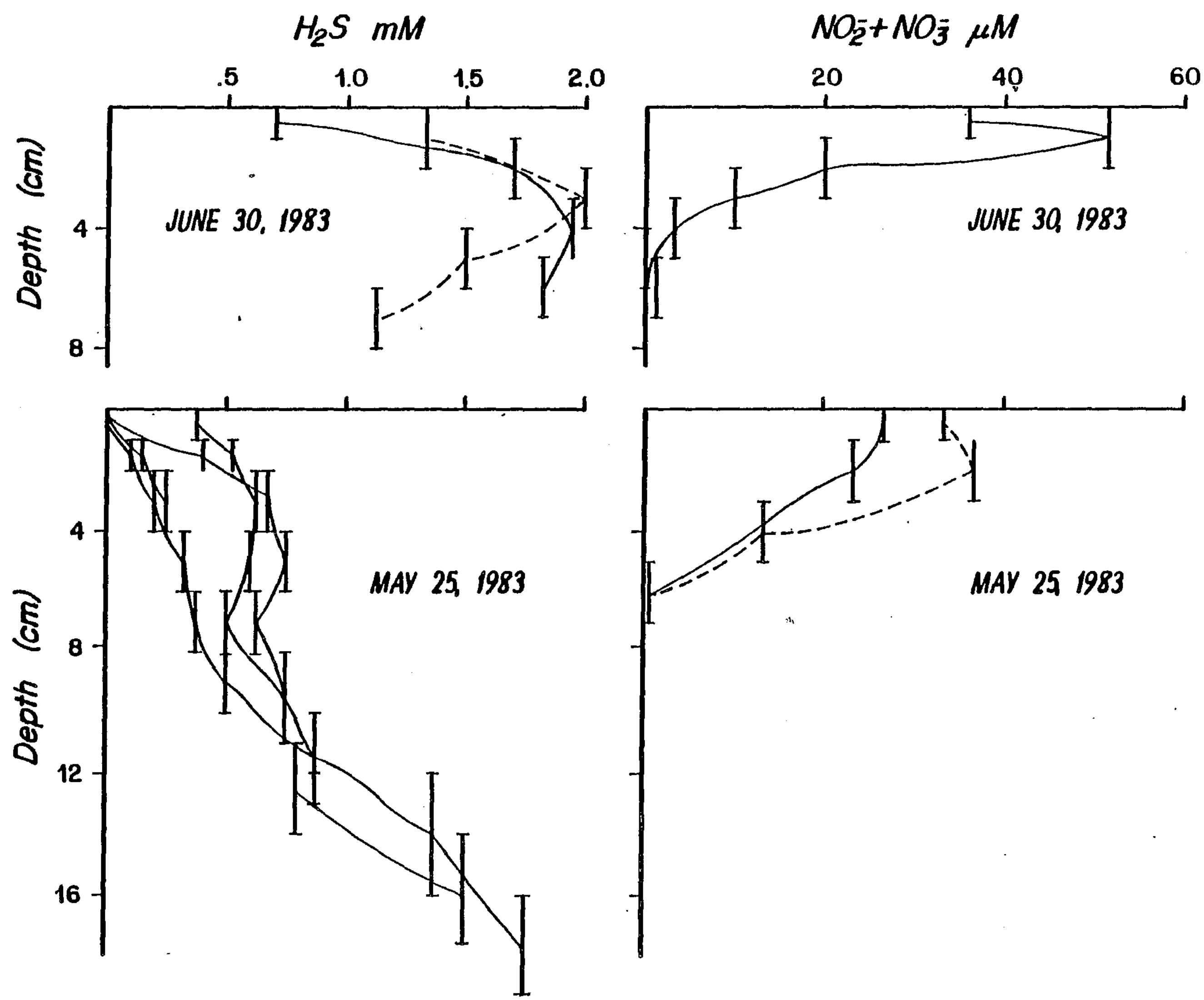


Figure 27. The concentration of hydrogen sulfide and nitrate-plus-nitrite in porewaters from a cores taken at Station 8 on June 30, 1983 and May 25, 1983. Vertical lines indicate the increment of the core analysed.

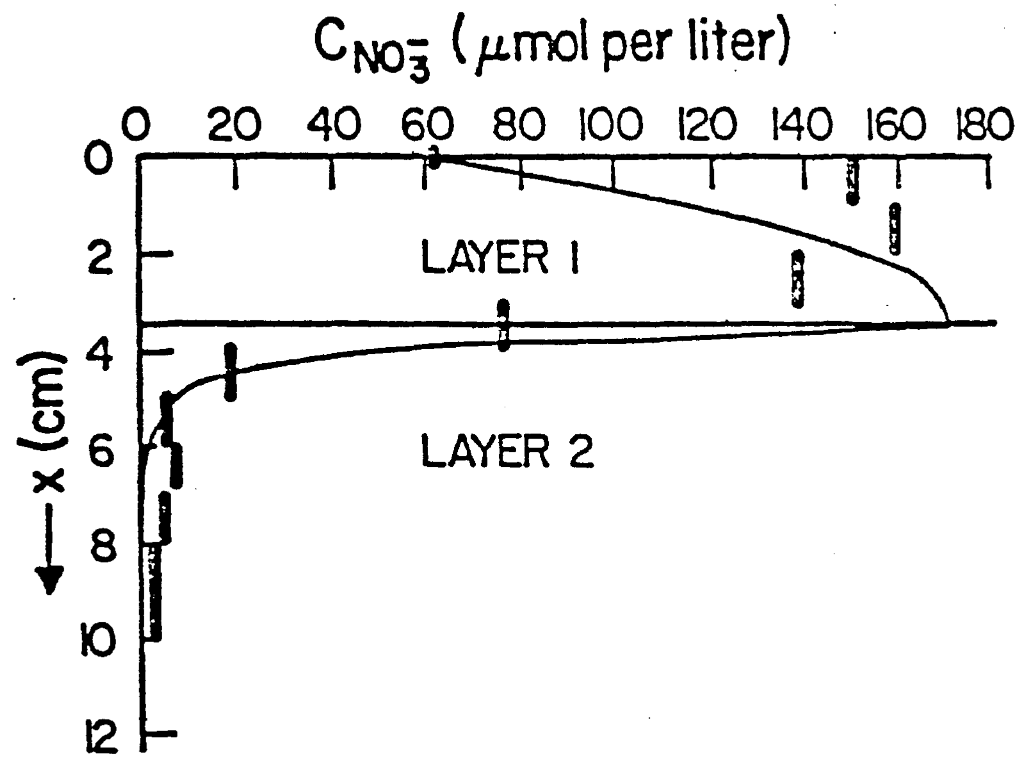


Figure 28. Fit of theoretical curve (two layer model) for dissolved nitrate to sediment data for Belgian coastal sediments (after Vanderborght *et al*., 1977).

B. Losses of Nitrogen by Burial

The amount of nitrogen buried per year in Town Cove can be estimated if the nitrogen content of sediment and the burial rate are known. The nitrogen concentration in the sediments below 10 cm is fairly constant at 0.3% as determined by direct measurements in this study. The burial rate is more difficult to determine. The normal procedure requires the measurement of a variety of radioisotopes, a methodology beyond the scope of this study. Instead, we estimated the age of depths in the core using lead concentrations as an indicator. Lead is introduced into the atmosphere by industrial processes and by the use of leaded gasoline (Fig 29). Much of this lead subsequently falls out of the air or is removed by rain and deposited onto the land or into water bodies. Lead falling into water bodies is rapidly removed by several processes and deposited in the sediments which, over the past 80 years have aquired a characteristic profile, reported in several widespread parts of the country. Cores taken from marine (Ng and Patterson 1982, Chow et al. 1973) and freshwater environments all show a dramatic increase in lead since 1900 (Figs. 30, 31). In general the increase in lead in cores matches the increase in the use of leaded gasoline, except near urban areas with higher traffic where higher levels of lead and the pattern of increase frequently mirrors the growth of population. Recently the amount of lead in sediments has begun declined due to a reduction in the lead concentration in gasoline in 1970, and perhaps declining gasoline use. By dating prominent features of this lead profile using radioactive isotopes, other studies have produced a lead chronology that can be used indirectly to arrive at ages in sediments where only the lead profile is known.

We took cores near station 8 to measure the amount of lead present at depth in the sediments (Fig 32). By comparing the profiles we obtained in Town Cove

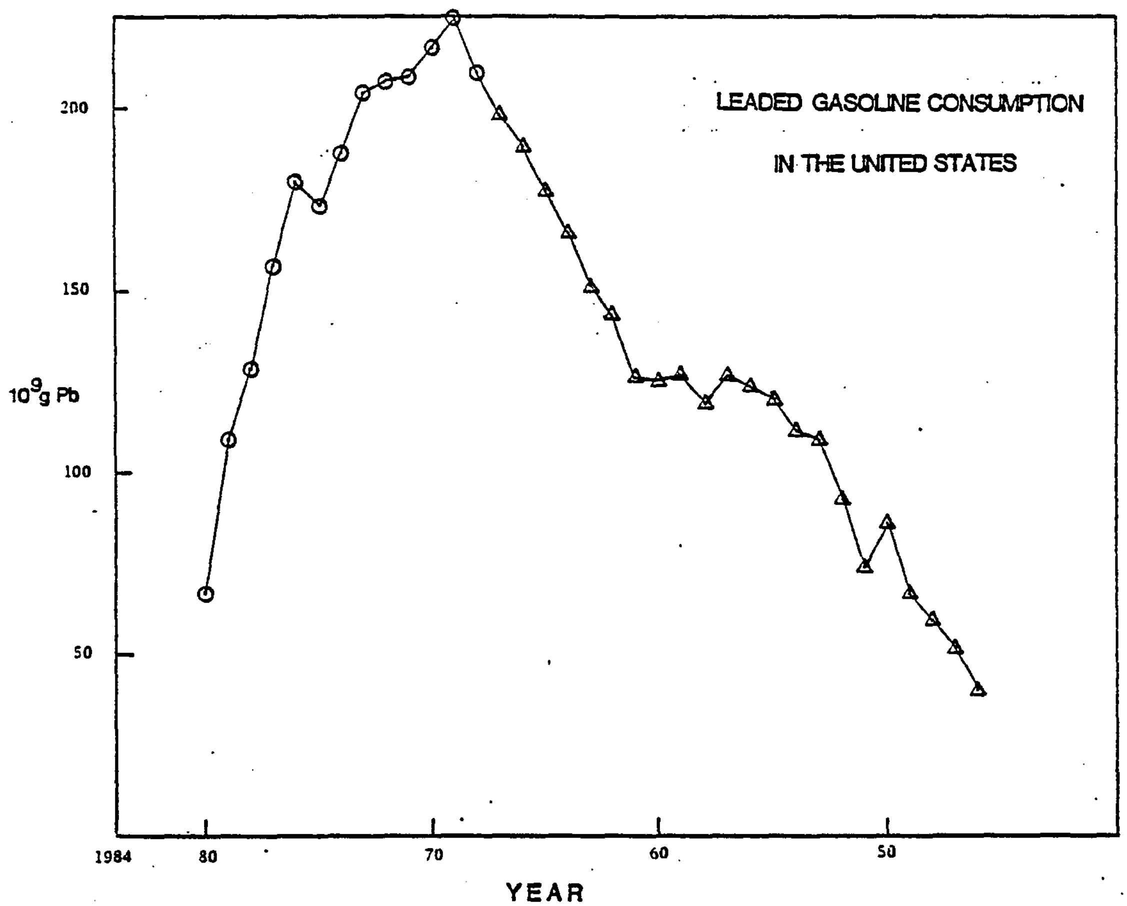


Figure 29. Leaded gasoline consumption in the United States.

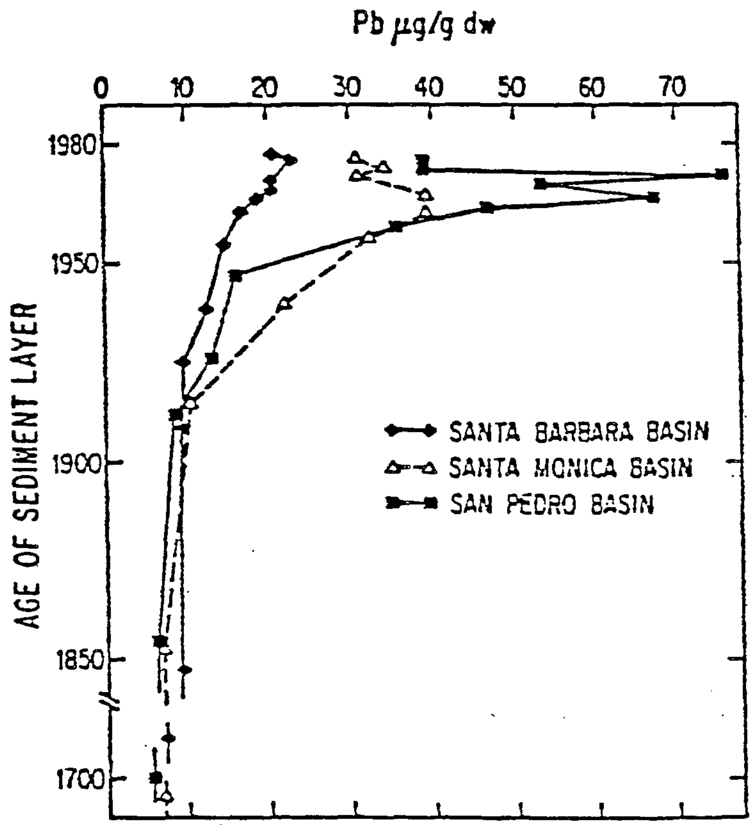


Figure 30. Lead concentrations in sediment from depositional basins off the coast of California (after Ng and Patterson).

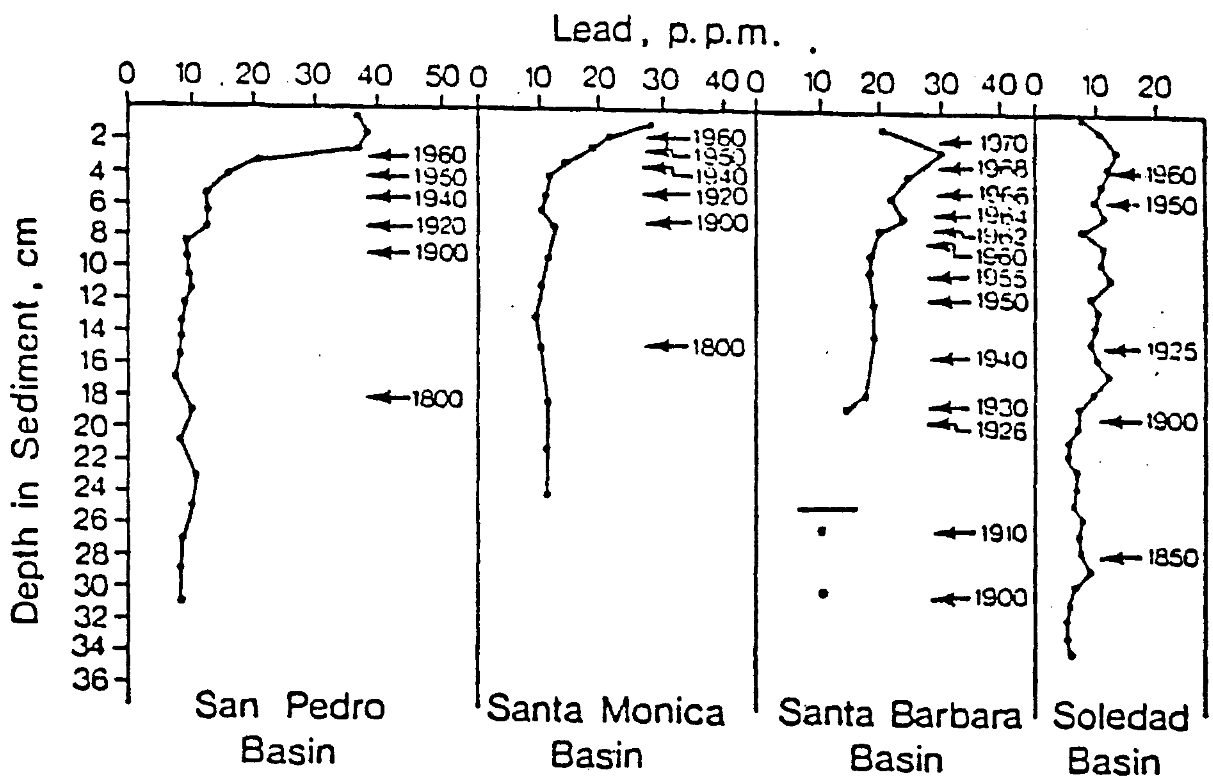


Figure 31. Lead concentrations in sediment from depositional basins off the coast of California (after Chow, 1978).

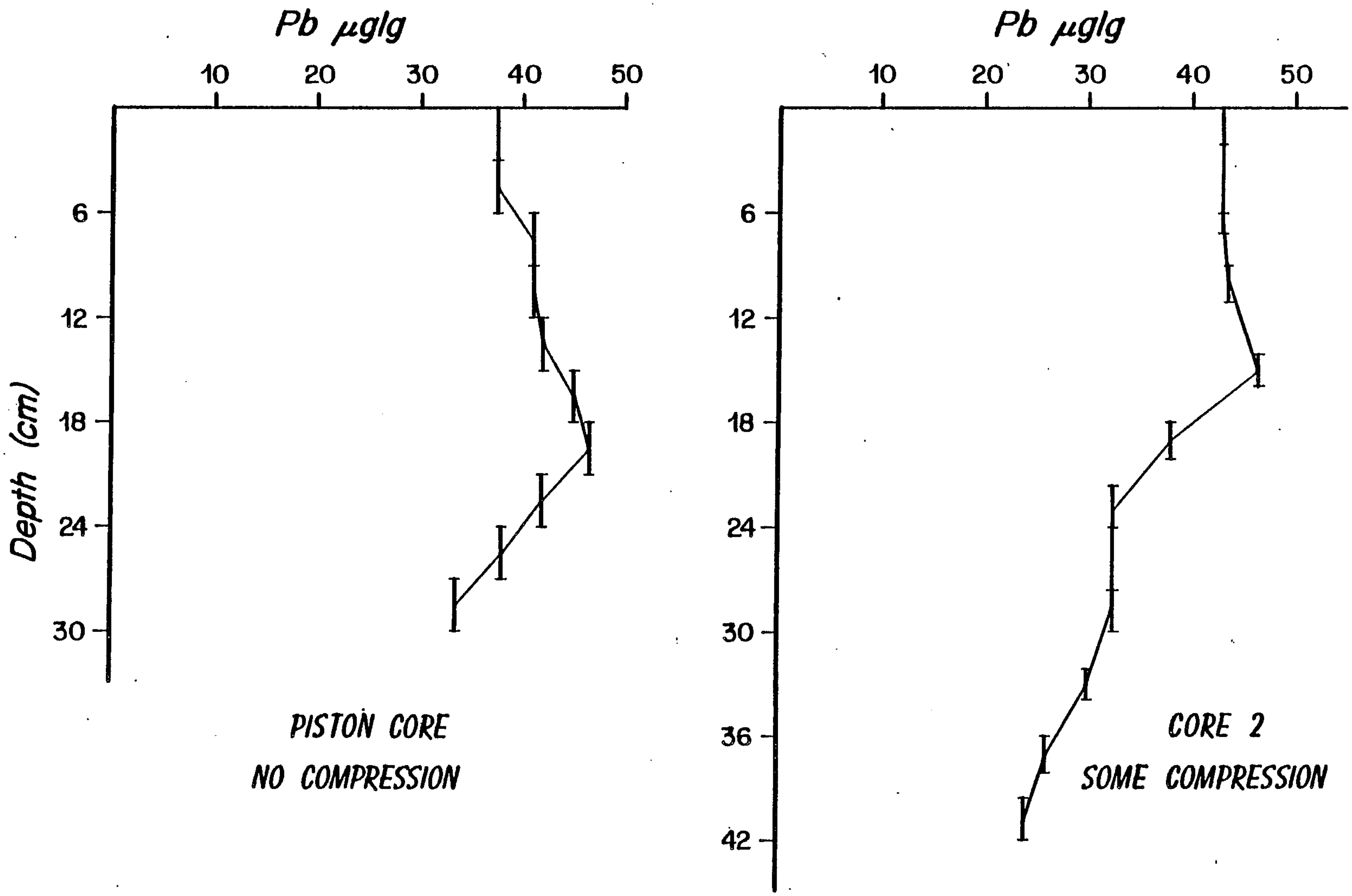


Figure 32. Lead concentrations in sediments from Town Cove, Mass., collected using a piston corer and a gravity corer, at stations 8 and 15. Vertical lines indicate the core increment analysed.

to other areas, and from our knowlege of population growth in the Lower Cape, we were able to estimate the sedimentation rate. One core was taken with a piston device and showed no evidence of compaction. The other core exhibited compaction and rates taken on this core were corrected accordingly. The cores were sectioned and oven dried. Two grams of material were leached in 10 ml of 1.6 N nitric acid for 24 hr to remove the lead. This is similar to the procedure used by Ng and Patterson (1982) and primarly removes lead introduced from the atmosphere and does not remove most of the lead associated with clay particles.

The results of this study show that sedimentation rates in Town Cove are quite high. At a depth of 40 cm we still see fairly high levels of lead, and since the levels continue to drop the sediments were deposited before 1900 when lead was essentially at background levels. We see a peak in lead in both the cores which we assume corresponds to about 1970 when the maximum amount of lead were being introduced into the atmosphere (Fig 29). Estimates of burial rate in the top of the core are not as useful as in the lower part of the core because the material is still compacting. However these estimates would indicate that the sedimenation rate is as high as 1.5 cm y^{-1}. We calculated the sedimentation rate in the lower part of the core by assuming the lead input is proportional to the population in the lower Cape area (background lead flux was neglected). The decrease in lead from the peak in core 2 (15 cm) to 41 cm is 52%. In 1970 the winter population in the lower Cape was 17,400, and in 1950 it was 8,700 (50% lower). Ignoring compaction in the core this would correspond to a sedimentation rate of 1.3 cm year. Correcting for compaction gives a rate of 1.8 cm y^{-1}. Making the same assumptions with the piston core the amount of lead at the bottom of the core is 71% of the maximum. Since the population in 1962 was roughly 71% of the 1970 population, this would correspond to a sedimentation rate of 1.3 cm y^{-1}.

The sedimented material has a dry weight density of 0.377g cm^3 at 20 cm and a nitrogen concentration of 0.3%. A sedimentation rate of 1.5 cm y^{-1} would correspond to a burial of 17 g of nitrogen M^2 y^{-1}. If we assumed that this is typical of the area of the cove below 3 M and then the yearly burial of nitrogen is on the order of 7650 kg N/y.

From these results, we conclude that the sedimentation rate in the Cove is on the order of 1.5 cm y^{-1}. There is a fairly large uncertainty is this number but it certainly lies within the range of 1-3 cm year. The nitrogen burial by sedimentation is on the order of 7650 kg N y^{-1}. This would correspond to a burial of 21 kg N/d.

C. Flux of Nitrogen from the Sediment to the Water Column

The flux of dissolved nitrogen from the sediments to the overlying water was measured in the cove. This nitrogen flux represents "recycled" nitrogen - nitrogen released by the decay of plants and animals. It is not 'new' nitrogen but its release is important since studies have shown that a large portion of the nutrients used a plankton can come from nutrients recycled by the benthos (Nixon 1981).

The benthic flux was estimated by two different methods. Benthic chambers were placed over the bottom and water was recirculated by use of a small electric pump (Fig 33). Samples of water enclosed by the chambers overlying the sediments were taken at intervals and analyszed for nutrients. The rate at which nutrients accumulated in the chamber head space, adjusted for chamber volume and the area of the bottom, gives the benthic nutrient release rate. These chambers were deployed during September, October, June and August near station 8 (usually from the Yacht club float).

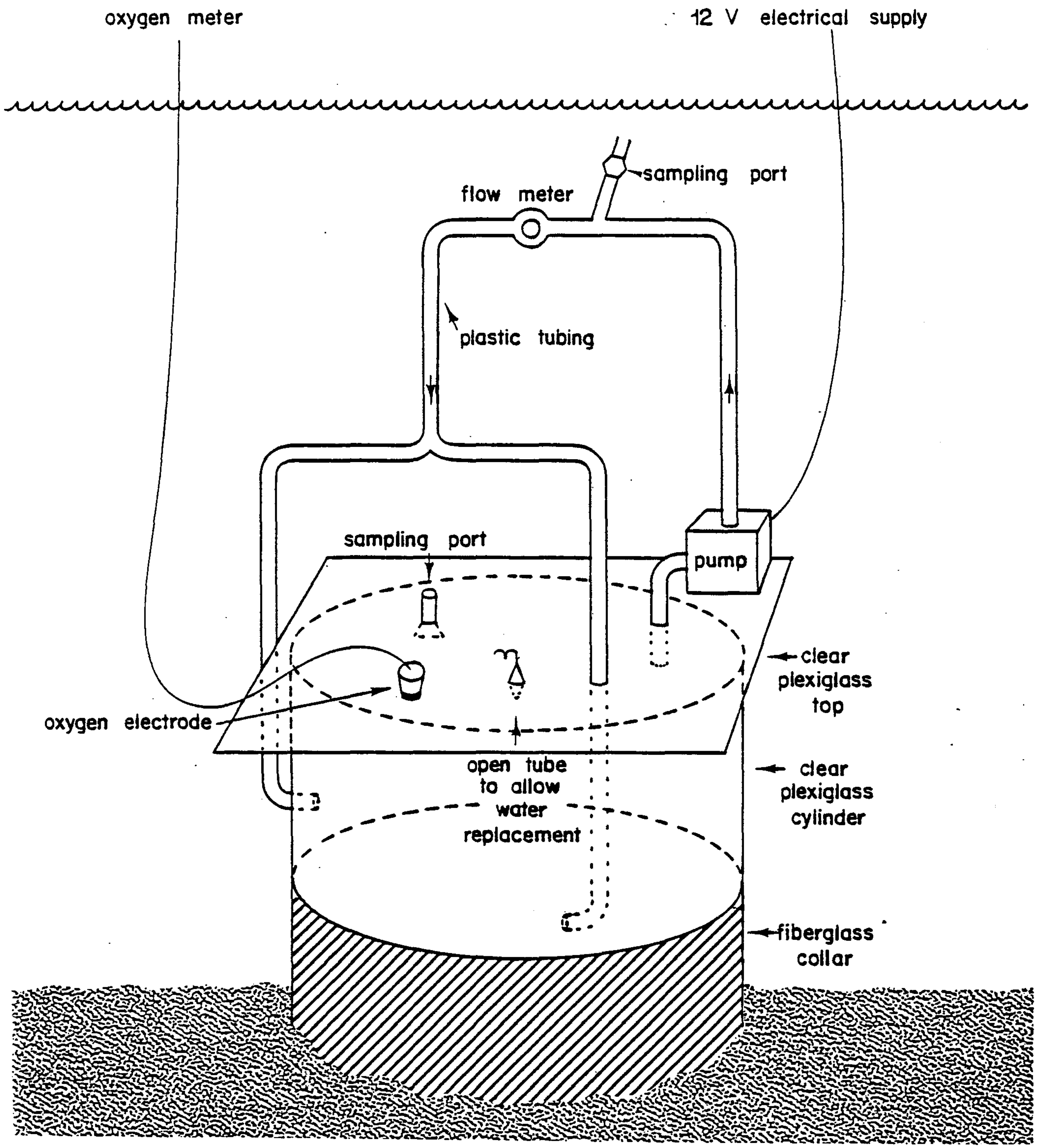


Figure 33. Diagram of the benthic chamber used to measure sediment-water column nutrient fluxes in Town Cove.

Fluxes into the chambers were usually linear (Fig 34). In some cases only 2 points could be obtained so linearity could not always be determined (Table 22). It was not always possible to see the bottom when deploying the chambers; when the bottom was visible it did not appear that there was any disturbance due to chamber placement, except for one chamber in the September run which clearly had been disturbed. Disturbance tends to underestimate porewater fluxes by forcing bottom water into the sediment and flushing out nutrients from the surface of the sediment. Since fluxes were normally linear this did not seem to be a problem, but if it occured it would cause our estimates to be too low.

Ammonia fluxes from the sediment were high. Chamber flux rates ranged from 453 uM M^2 h^{-1} in October (about 213 Kg N/day for the Cove) to a high of 1061 um M^2 h^{-1} in August (about 500 Kg N/day for the entire Cove). Nitrate fluxes were low and quite erratic. Nitrate would sometimes accumulate in the chamber and then disappear. We have assumed that the nitrate flux was zero in our calculations.

The flux of ammonia from the sediment was also calculated from porewater gradients (see Appendix II). The ammonia concentration at different depths in the sediment provided information on the gradient, and flux was calculated using porosity and diffusion coefficients. Cores were taken in October, December, March, May, June and August (cores for October, June and August were taken along with chamber measurements). Calculated fluxes from both methods are in close agreement (Table 23, and Fig 35). Fluxes calculated from porewater gradients are usually lower than the chamber flux values since they do not take into account other processes such as the stirring of the sediment by macrofauna. There were almost no macrofauna in the sediments during the time when the comparisons were made, according to Mr. G. Hampson, a benthic

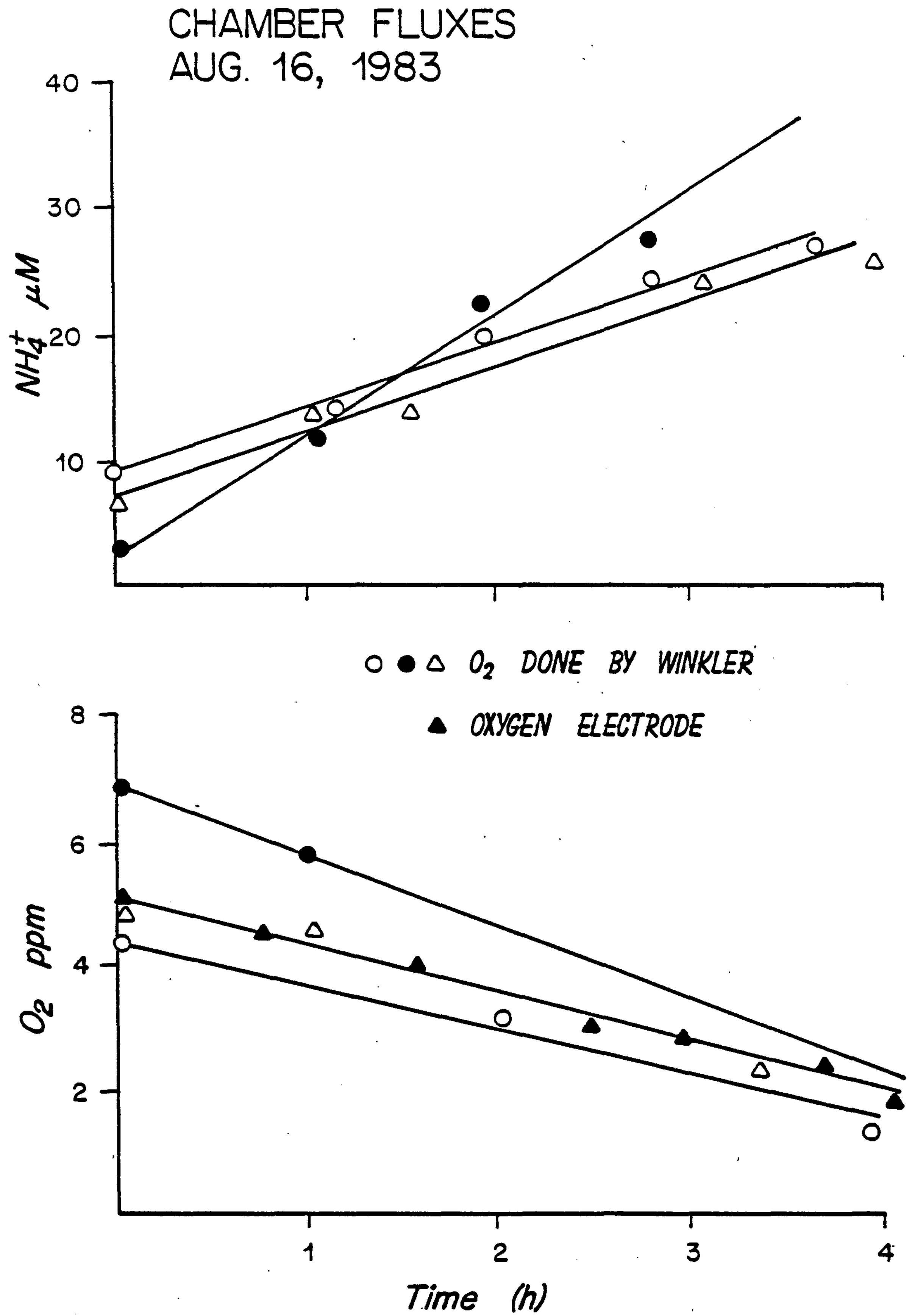


Figure 34. Change in ammonium and oxygen concentrations in the head space of three chambers deployed in Town Cove, Mass., during August, 1983.

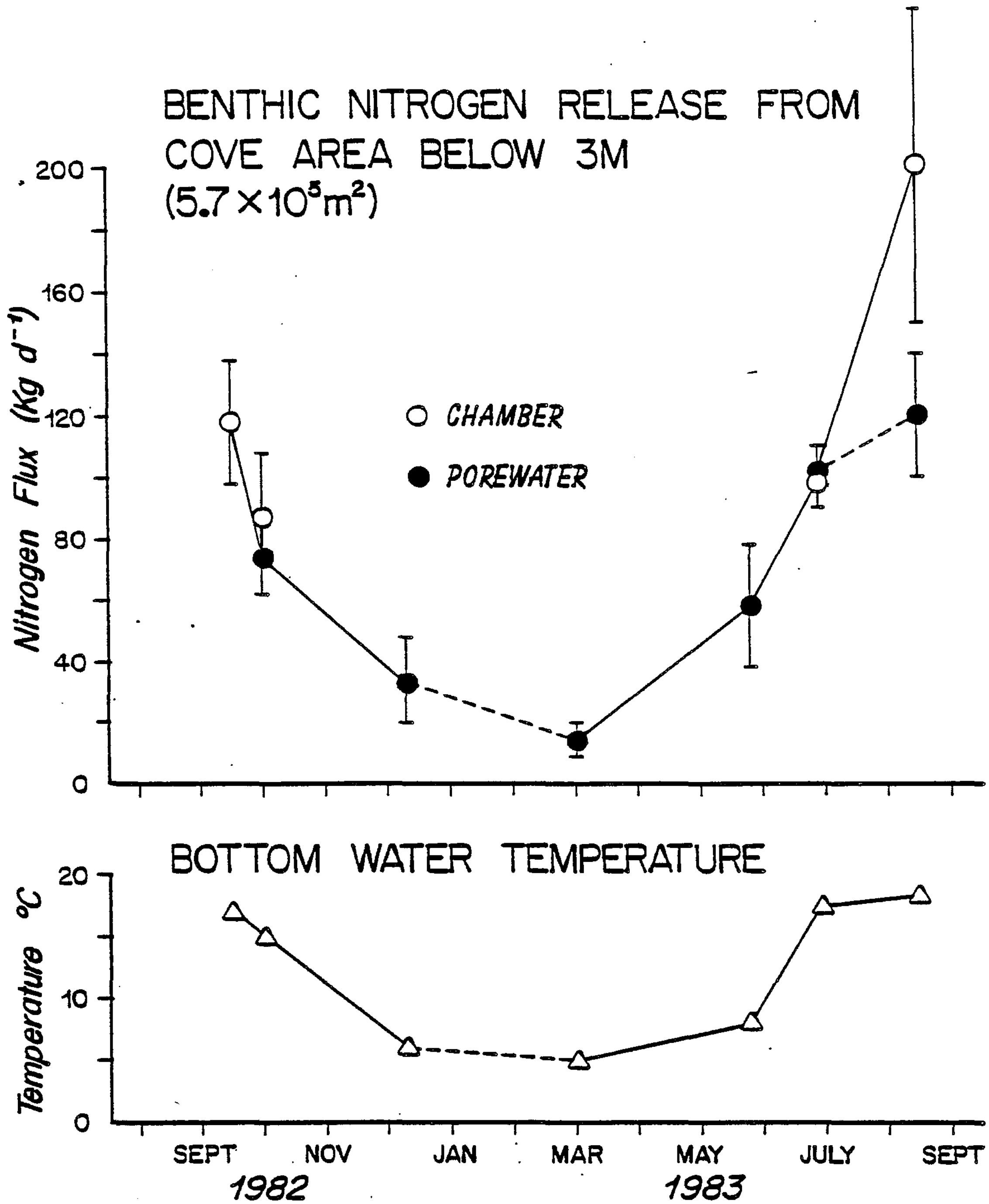


Figure 35. Nitrogen flux from the bottom of Town Cove, Mass., beneath 3 m depth, as calculated from porewater gradients and as measured in benthic chambers.

Table 22. Ammonia fluxes measured from benthic chambers placed near Station 8.

Date	Temperature	Chamber #	# Points	Linear	Flux um m^2 h^{-1}
09/16/82		1	3	No*	<200*
	16.8°C	2	3	Y	516
		3	3	Y	710
	Mean ± S.E.				613 ± 103
10/01/82		1	3	Y	610
	15°C	2	3	~Y**	485
		3	2	-**	264
	Mean ± S.E.				453 ± 101
06/30/83		1	7	Y	395
	17.5°C	2	2	-**	569
		3	4	Y	627
	Mean ± S.E.				530 ± 70
08/15/83		1	5	Y	787
		2	5	Y	821
		3	4	Y	157Y
	Mean ± S.E.				1061 ± 257

*Clearly disturbed values not used in calculations
**Motor stopped at some time during run

biologist who examined these sediments as part of this study, which is probably why the agreement is so close. Macrofauna were present in May so the flux calculated from the gradients is a minimum estimate.

Using data from chambers and porewater gradients we calculated the release of nitrogen to the cove from the sediments. The area where we deployed the chambers is fairly typical of the muddy sediments in the deeper parts of the cove. Cores have been taken in several areas in the deeper parts of the Cove and all showed similar porewater profiles. We have assumed that these fluxes are typical of the area of the cove which is deeper than 3 meters. The total area of the Cove deeper than 3 meters is 5.7×10^5 M^2. The daily flux of nitrogen from this area of the cove ranged from 14 kg/day in the winter to 204 kg/day in August (Table 24). The flux of nitrogen is temperature dependent because it is the product of bacterial processes which slow down in the colder months of the year. We have coverted the daily rates for 7 months of the year to a year flux rate: 26000 kg /year (Table 24). Again, we should stress that this is nitrogen which has been recycled and does not represent new nitrogen, although it does provide nutrients for the plants growing in the cove, and helps support the high rates of productivity which we observed.

These measurements were from the deeper areas of the Cove. There is also a release of nitrogen from the shallower areas of the Cove. Our porewater measurements showed that there is some remineralization occuring in the sandy sediments (denitrification section). One set of chambers was deployed in these areas in September. Uptake by phytoplankton rapidly depleted the nitrogen in these chambers. Since uptake was faster than remineralization we knew these areas had fairly low fluxes so we concentrated on other areas. In September and October measurements were made in the eel grass beds near the main

Table 23. Values used to calculate ammonia flux from porewater data.

Date	Core #	Temp °C	2C/2Z/7=0		D_o	Flux um cm^2 h^{-1}
0/01/83	1	15°C	1049	.860	13.8×10^{-6}	385
	Mean ± S.E.					385
02/09/83	1	6°C	151	.820	12.2×10^{-6}	59
	2		971	.803		274
	3		661	.780		176
	Mean ± S.E.					170 ± 62
03/30/83	1	5°C	189	.877	11.8×10^{-6}	61
	2		242	.856		76
	3		217	.849		66
	4		264	.869		85
	Mean ± S.E.					72 ± 5
05/25/83	1	~8°C	199	.959	13.0×10^{-6}	86
	2		980	.972		433
	3		1208	.950		510
	4		424	.969		186
	Mean ± S.E.					304 ± 100
06/30/83	1	17.5°C	1352	.871	16.8×10^{-6}	621
	2		968	.885		456
	Mean ± S.E.					539 ± 83
08/15/83	1	18°C	1101	.899	17.0×10^{-6}	522
	2		1536	.907		728
	Mean ± S.E.					625 ± 103

Table 24. Flux of Nitrogen from the sediment to the overlying water from the area of the cove deeper than 3 meters (5.7×10^5 m^2).

Month	Flux Kg n/d	
	Chamber measurements	Porewater gradients
September	118	–
October	87	74
November	–	(>50)*
December	–	33
January	–	–
February	–	–
March	–	14
April	–	–
May	–	58
June	102	103
July	–	–
August	204	120

*NH_4^+ values off scale on assay based of minimum possible values.
Total flux = 25995 cg/y

channel. At this site in October, the rate of ammonia release from the sediment averaged 50 $uM/m^2/hr$. This rate corresponds with a release of 7 Kg N/day into the entire Cove. This is less than 10% of the flux measured from the deeeper areas of the Cove, so no further measurements were made at the shallow sites. It does point out however that our estimates of benthic release are minimum estimates.

D. Anoxia in Town Cove

Oxygen is required by plants and animals. When oxygen levels in water fall to low levels, animals such as fin- and shellfish are adversely affected. The amount of oxygen present in water is much lower than in air and the solubility of oxygen is lower in warm water than in cold water. In addition, respiration (which uses oxygen) by plants, animals and bacteria is greater at higher temperatures. For this reason lack of oxygen (anoxia), if it occurs at all, is most likely to be a problem in the summer months. We took measurements of oxygen, temperature, and salinity in several locations in Town Cove over a 24 hour period to determine if anoxia occurred. Measurements were made in August, September, and October, 1982 and March, April, June, and August 1983.

We have reported on results from many of these studies in the previous progress reports (Teal et al, 1982, 1983). The pattern we observed this spring and summer was similar to what was previously reported. Bottom water in the central sections of the cove is usually colder, saltier, and lower in oxygen than the surface waters. In the spring when water temperatures are low (Fig. 36) the difference in the oxygen content in the surface and bottom water is not as pronounced as it is in the summer (Fig. 36). Our measurements show that the bottom water does occasionally go anoxic in the deepest regions of the Cove. Permanent anoxia does not develop because even the deepest areas of the cove are periodically ventilated through mixing or tidal action (see Aubrey, this report). According to observations of Mr. G. Hampson, certain worm species are absent from the deepest part of Town Cove during certain months as a result of inadequate oxygen. We are not aware of any fish kills or death of shellfish resulting from this condition The shallower areas of the cove are well mixed by tidal flow and do not experience oxygen depletion in the water column. This condition is also known to prevail in a number of similar ponds on Cape Cod, such as Oyster Pond, Salt Pond and Sider's Pond in Falmouth, as well as a number of coastal ponds in Rhode Island and elsewhere in New England. It is known that some of these ponds are permanently anoxic, and that others have been this way for more than a thousand years.

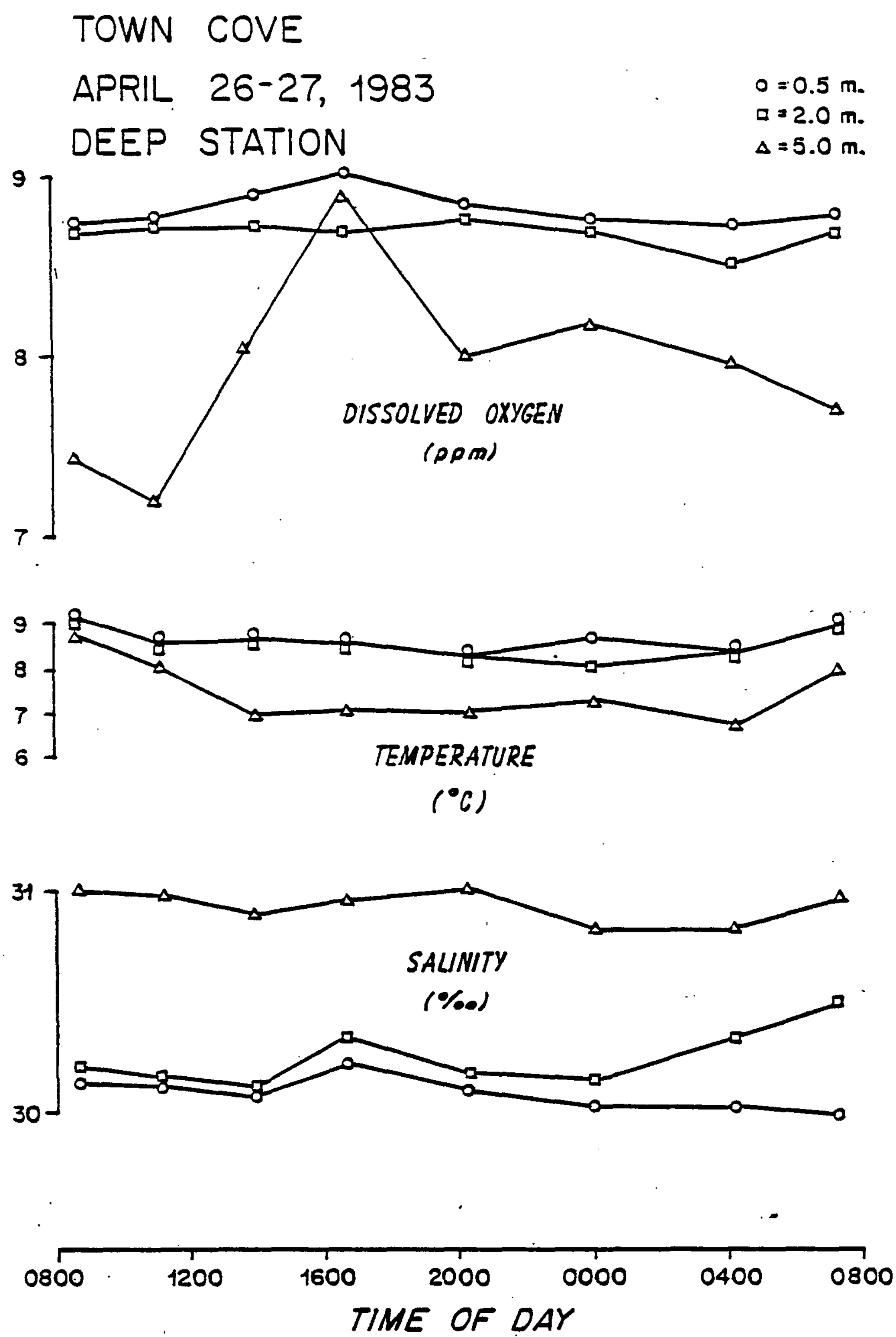


Figure 36. Changes in oxygen, temperature, and salinity over a 24-hour period at Station 8, Town Cove, Mass. June 29-30, 1983.

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Physical Modeling

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The goals of the physical modeling task were to describe the water exchange characteristics between Town Cove and the adjacent estuarine waters, and to define the mixing within Town Cove itself on a seasonal basis. Because of the importance of the bathymetry of Town Cove and the adjacent estuary to mixing and exchange processes, the bathymetry was mapped accurately as part of this task. Then, numerical modeling efforts were combined with field measurements to derive a descriptive model for both tidal exchange rates and mixing processes (described below). This dual approach has allowed us to place bounds on the accuracy of our data, and determine variability within our estimates. These results have been used to estimate both nutrient fluxes and salt balances between Cove and estuarine waters. Salt balances allowed us to estimate net freshwater inflow into Town Cove groundwater.

A. Bathymetry

We have prepared a bathymetric chart for Town Cove based on precision echo-sounding and navigation (Fig. 37). Depths were determined using a Raytheon DE719B precision echo-sounder, operating at a frequency of 200 kHz, with a narrow-beam transducer. Measured depths were corrected to a mean tide level using three Sea Data Corporation TDR1-A pressure/temperature sensors, located throughout Town Cove. The datum of the chart is mean water level for the time period of the tidal measurements, which is within 10 cm (4 inches) of the yearly mean tide level. Although somewhat arbitrary, this datum should be sufficiently accurate for most purposes. Navigation for the bathymetric

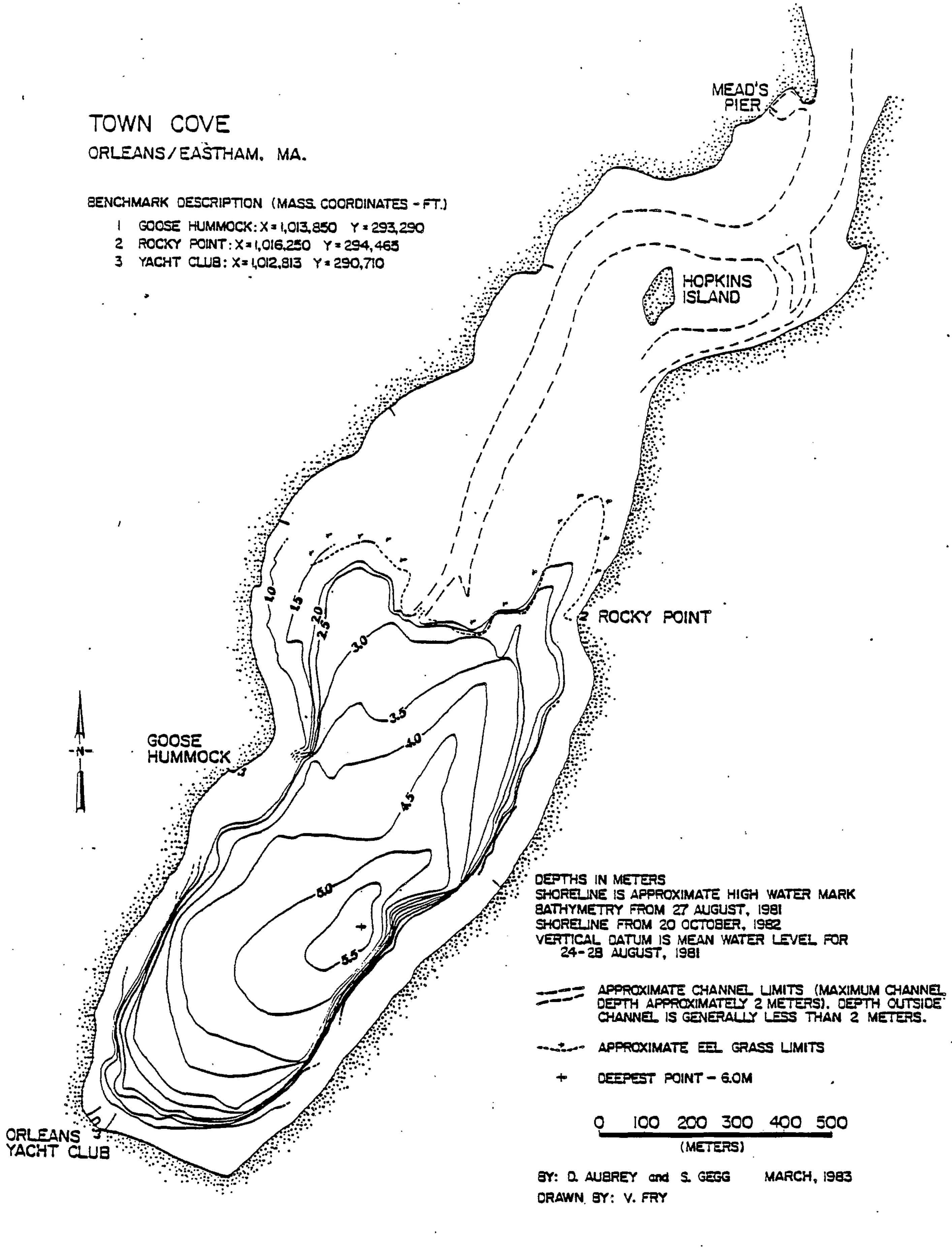

Figure 37. Bathymetric map of Town Cove and feeder channel.

survey was accomplished with a Del Norte Trisponder system, using a master station on the survey vessel and three land stations at Goose Hummock, Rocky Point, and the Orleans Yacht Club (Fig. 37). Navigation data is stored on a magnetic cassette tape, which is then merged with bathymetric measurements and tidal elevations, as well as a depth correction (to correct for draft of our vessel). This data is used to generate a computer plot of measured depths, which can then be contoured either by hand or by computer. The result is a bathymetric chart (Fig. 37). The shoreline is an approximate location of high tide derived from a map-quality set of vertical aerial photographs taken in October 1982, by a professional aerial mapping firm (Col-East, Inc., North Adams, MA). It was enlarged to fit the scale of the bathymetric chart and superimposed. Its positional accuracy is within 5 meters (root-mean-square error).

The bathymetric detail within Town Cove itself is excellent, with a maximum depth of 6 m in the deepest part of the Cove. Depth detail of tidal channels leading into Town Cove is shown schematically, for a number of reasons. Since the channel bathymetry is complicated, an inordinate amount of spatial coverage would be required to map the area precisely. Most use of the chart, however, requires no such detail, but rather only requires the position and approximate depth of the main channel. We have decided to provide that information in a schematic form in an effort to make the chart more readable and useful.

B. Tidal Exchange

A combination of field measurements and numerical modeling were used to define the tidal exchange between Town Cove and the connecting estuary. Field measurements were obtained using pressure sensors, a five-element array of current meters, and tide gages. Numerical modeling included both one- and two-dimensional schemes, emphasizing the roles of continuity and momentum exchange between Town Cove and the estuary, but not detailing dissolved or suspended material transport.

Two tide stations (Fig. 38), established in Town Cove in July, 1982, were maintained for the duration of the study. The tide gages, Leupold-Stevens Model No. 71-A, were on loan to the project from the U.S. Army Corps of Engineers, Coastal Engineering Research Center. The day-to-day operation of these gages was checked by Mr. Larry Ellis, Mr. Jim Rewett and Ms. Sandra Libby, of the Orleans Harbormaster/Shellfish Department.

The tide gage information was used for a number of purposes, some of which are discussed here. First, the tide gages provided sea surface reference for correcting bathymetric surveys to a common datum, a necessary step for making a bathymetric chart. Second, since the tidal information was used to drive the numerical model of circulation in Town Cove, it was required for evaluating seasonal differences in tidal forcing, as well as providing accurate water flux estimates for periods of intense biological and chemical sampling. Finally, the tidal measurements allowed us to describe mathematically the tide in Town Cove.

Tidal analysis consists of examining a tidal record mathematically to separate out the 25 to 37 major tidal elements which are responsible for tidal behavior at any specific location. These major tidal elements (constituents) are the product of both sun and moon gravitational attraction, as well as local effects due to the configuration of a particular water body. Mathematical

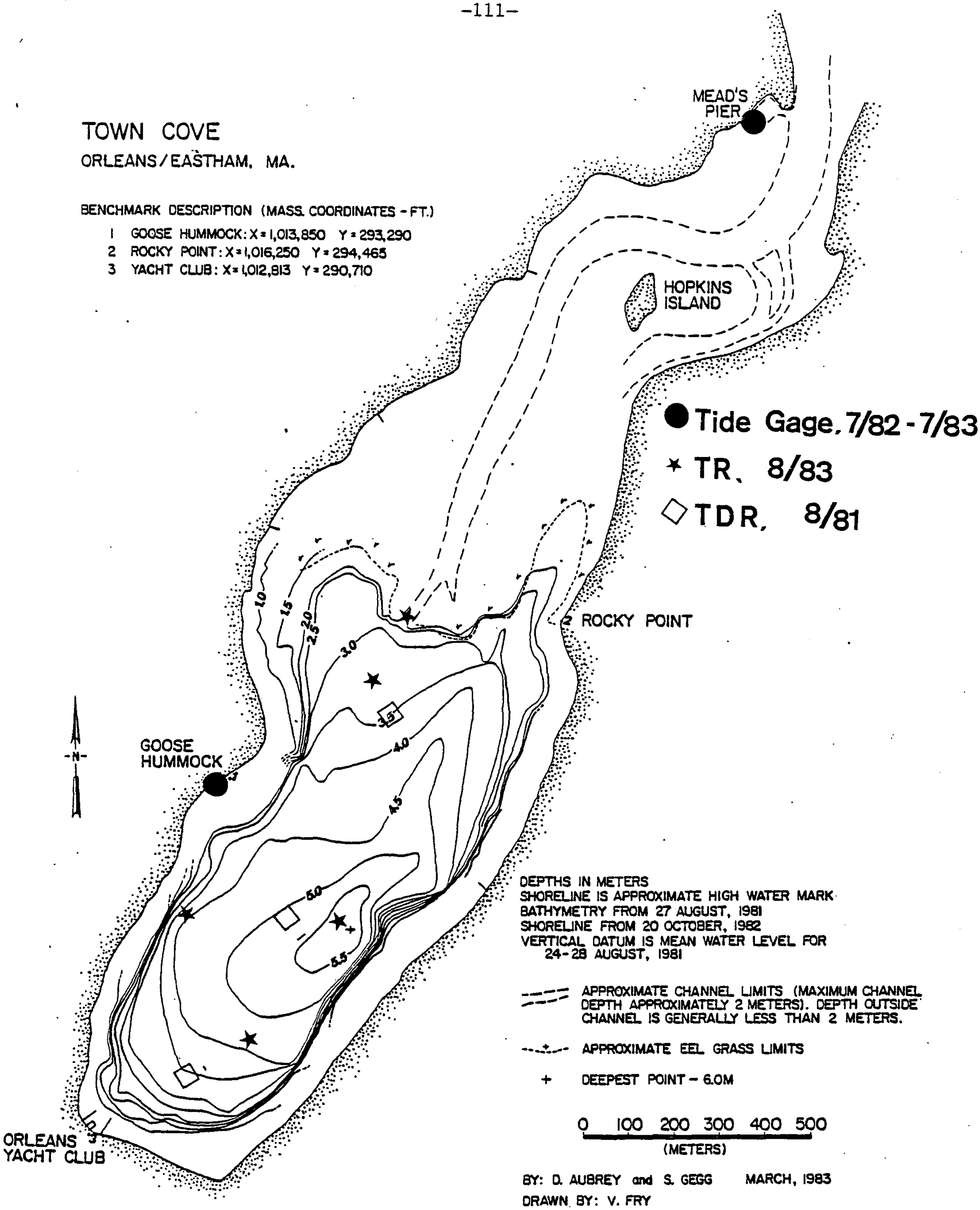

Figure 38. Location map for tide gages (July 1982-July 1983), TDR's (August 1981), and TR's (August 1983).

separation of the different constituents from the tidal data is accomplished using methods of Schureman (1971), as implemented on digital computers by Dennis and Long (1971) and Boon and Kiley (1978). These latter programs have been modified to improve consistency and accuracy on our computer. The result of this type of analysis (harmonic analysis) is a description of 25 different tidal constituents, combined with their relative amplitudes and phases. This information allows us to predict tides at any former or future time period, for that specific location. Tidal constituents for Town Cove and Mead's Pier are listed in Appendix III.

Based on harmonic analysis over several 29-day long records for both Mead's Pier and Goose Hummock tide stations, we determined the mean tidal range for Town Cove to be 1.2 m, which is nearly identical at both stations.

The tide gage records can be used to calculate discharge in and out of Town Cove, using a simple differencing technique. The curve labelled continuity model in Fig. 39 was calculated from this approach, using Mead's Pier tidal information. The continuity model assumes a constant surface area (A) for Town Cove and the nearby channels over a tidal cycle. Because Town Cove does not have extensive tidal flats, this assumption is justified. The water flux or discharge (Q) past Mead's Pier can then be approximated as the product of Town Cove surface area (A) and the time rate of change in the surface elevation (η):

$$Q = \frac{\Delta\eta}{\Delta\tau} \cdot A$$

This model was used to estimate discharge during periods of intense biological or chemical sampling.

To use the model results with confidence, sea level in Town Cove must

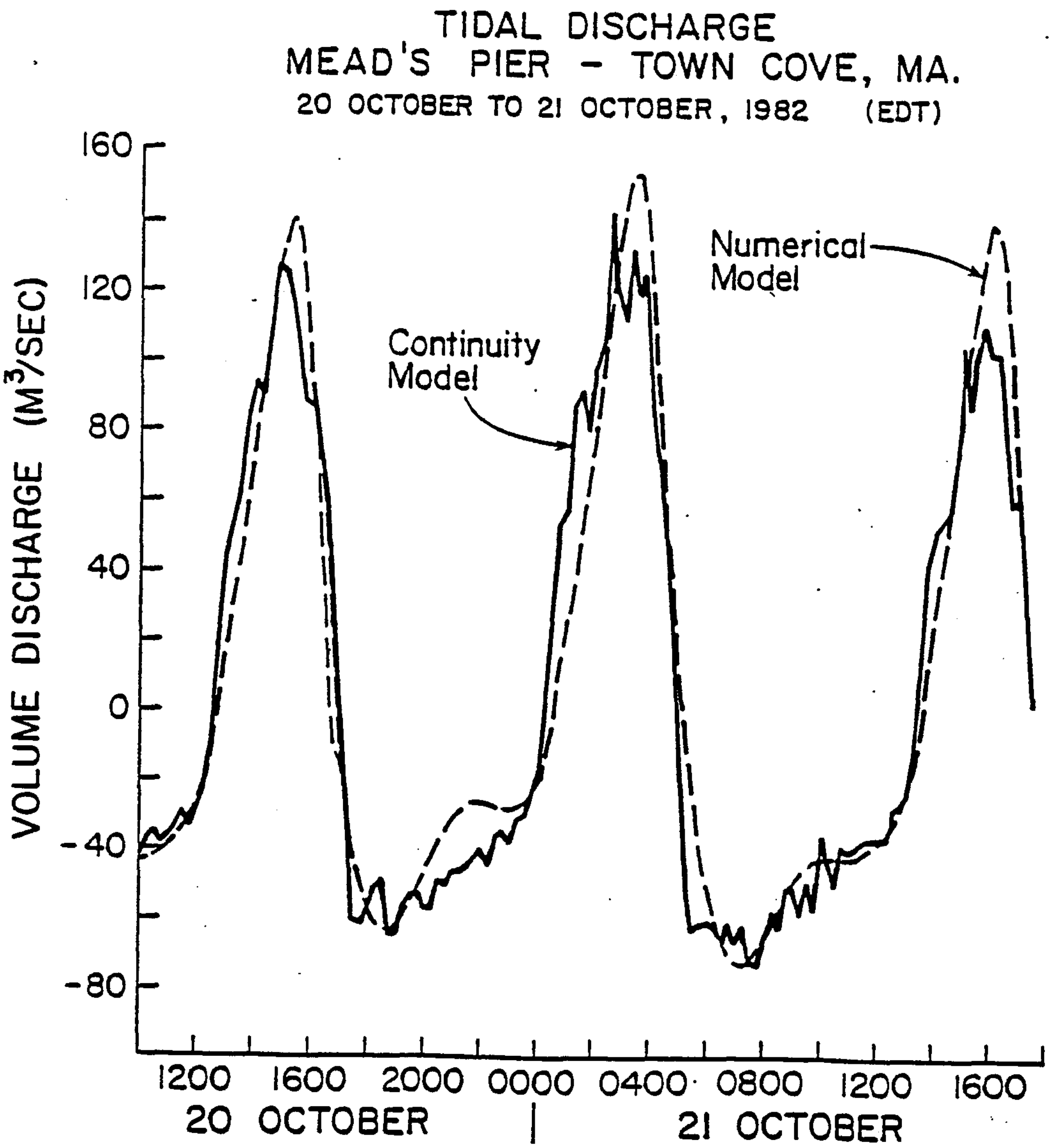

Figure 39. Tidal discharge past Mead's Pier was calculated from two independent models. The continuity model is calculated knowing the time derivative of tidal height and the total drainage area; the numerical model is two-dimensional, and based on the grid of Fig. 43. The close match in phasing of the discharge curves suggest we have the physics of tidal flow modeled correctly; the underestimation at peak flood discharge reflects the uncertainties in the two models.

remain horizontal, without significant lateral gradients in water level. This certainly is not the situation in the remainder of the Nauset estuary, as shown by a comparison of tidal range at various points through the channels leading into Town Cove (Fig. 40). To test the hypothesis that Town Cove sea surface remains horizontal over a tidal cycle, three pressure sensors were installed for a one-week period through Town Cove to examine horizontal gradients in water level (Fig. 38). The results show that Town Cove rises and falls with the tide as a unit, with little water surface tilt except perhaps during periods of high winds. This experiment helps justify a continuity model for calculating discharge. A related piece of evidence supporting this conclusion is the lack of significant time lag in tidal response between the Mead's Pier and Goose Hummock tide stations, as well as their equal tidal amplitudes.

Finally, numerical models were developed to investigate the water flow into and out of Town Cove, in part, to examine the utility of the continuity model in estimating tidal flux at a particular segment of time. The numerical modeling program involved a study of the tidal circulation within Town Cove as well as investigation of the mechanics of tidal propagation through the southern drainage channels of the Nauset estuary. Several numerical models were developed to examine these problems. A one-dimensional (cross-sectionally averaged) model of the southern drainage channels including Town Cove was used to study the generation of tidal asymmetries within the estuary (Aubrey and Speer, 1983a, b; Speer and Aubrey, 1983). A two-dimensional (depth-averaged) model was constructed to examine the barotropic response of Town Cove to tidal forcing.

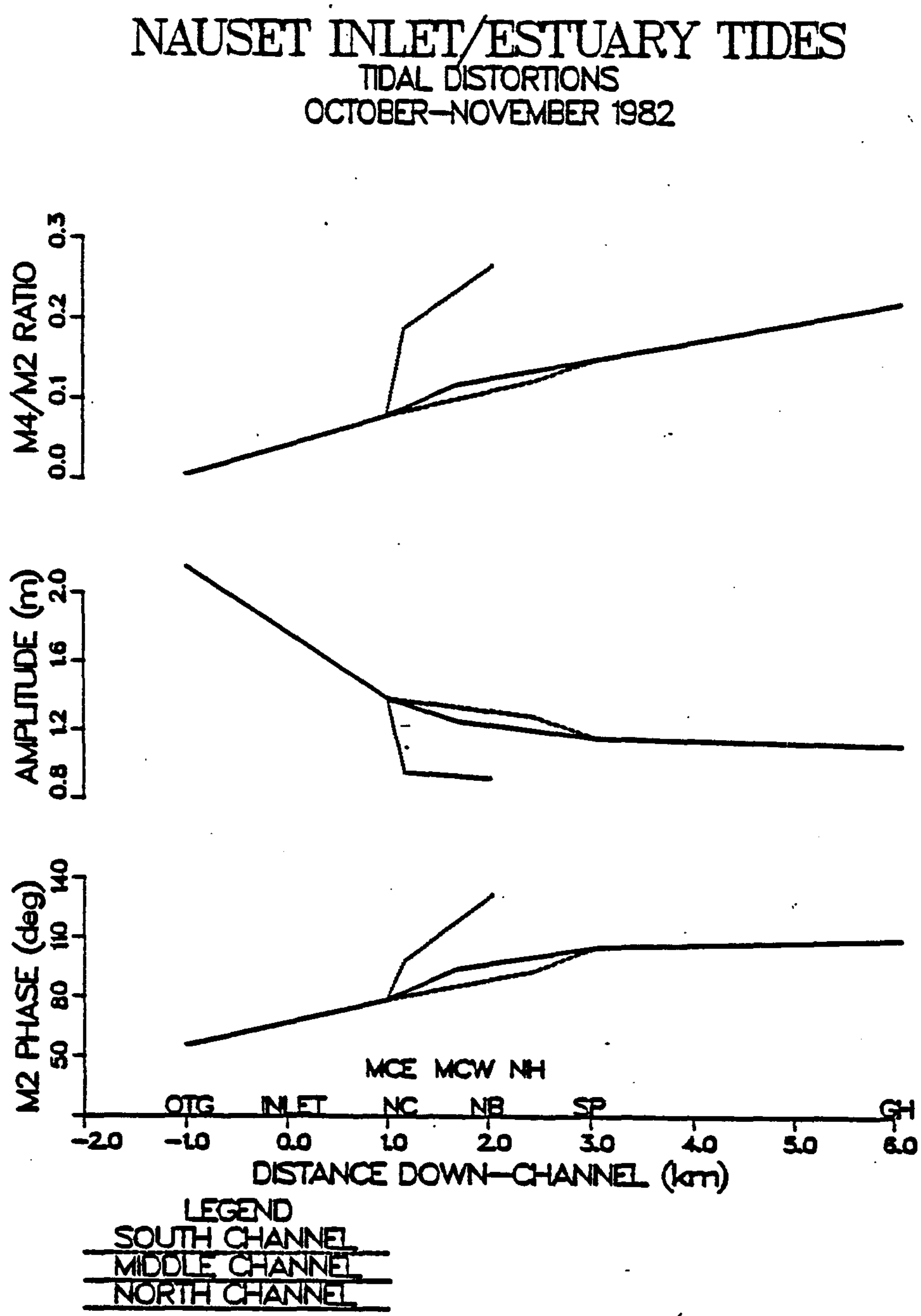

Figure 40. Tidal distortion from the ocean proper through the three major channels of the estuary. Top panel shows the increase in ratio of M_4/M_2 tidal amplitudes with distance into the estuary. Largest ratio is in Nauset Bay, along North Channel. Second panel shows mean range of total tide as a function of distance into the estuary. Most rapid decay is along North Channel, least rapid decay is along South Channel. Lowest panel shows phase of M_2 tide throughout the estuary, referred to a local tidal epoch. Most rapid phase lags take place in North Channel, least rapid in South Channel.

The tide is strongly distorted by the time it reaches the channel approaches to Town Cove. Falling tide exceeds rising tide in duration by 3-4 hours. As a result, the pattern of tidal currents in the channel near the cove is characterized by a long, slow ebb and a fast, short flood (Fig. 41). This asymmetry in the tide has important implications with respect to circulation and mixing within the Cove. In particular, it will cause a bias in the direction of transport of suspended particulate material into the cove. Utilizing one-dimensional models of the southern estuarine channels, we have been successful in reproducing the distinctive character of tidal currents near Town Cove (Figs. 41 and 42). The fluid mechanical reasons for the asymmetric tide at Town Cove are related to strong frictional effects in the channels and the highly variable cross-sectional areas of the channels over a tidal cycle. The important point is that the structure of the tide at Town Cove is controlled by physical characteristics of the channels connecting the Cove to Nauset Inlet.

Tidal circulation in Town Cove was investigated with a two-dimensional (depth-averaged) model of the Cove and its channel approaches. Fig. 43 shows the extent of the modeled region and the numerical grid employed by the model. The numerical model is an explicit finite-difference scheme: temporal derivatives are approximated by forward time steps and spatial derivatives by centered differences. The model equations are presented in Appendix IV for those interested in the mathematical detail. A depth-averaged model has some limitations when strong vertical stratification is present in the water column. Because of vigorous tidal mixing this situation never occurs in the channels but will occur during the summer within the Cove. Since the results are used largely for discharge purposes, this limitation is not crucial.

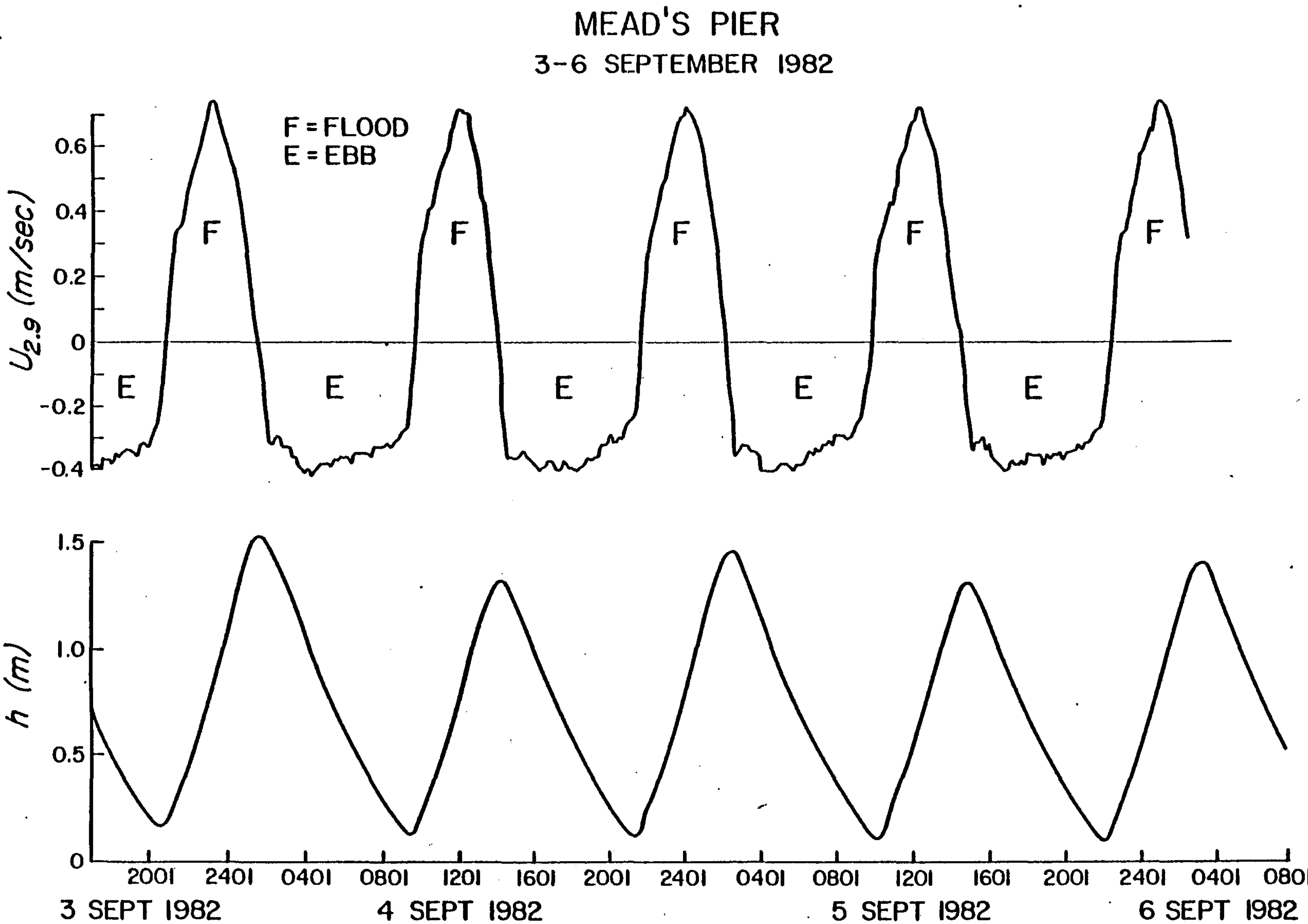

Figure 41. Measurements of velocity (top panel) and sea surface elevation (lower panel) for 2 1/2 days, acquired in feeder channel leading into Town Cove (Mead's Pier, Fig. A). Velocity is at top sensor (2.9 m [9.5 feet] above bottom in 3.5 m [11.5 feet] water depth) of five element array. Sea surface is with respect to an arbitrary reference level.

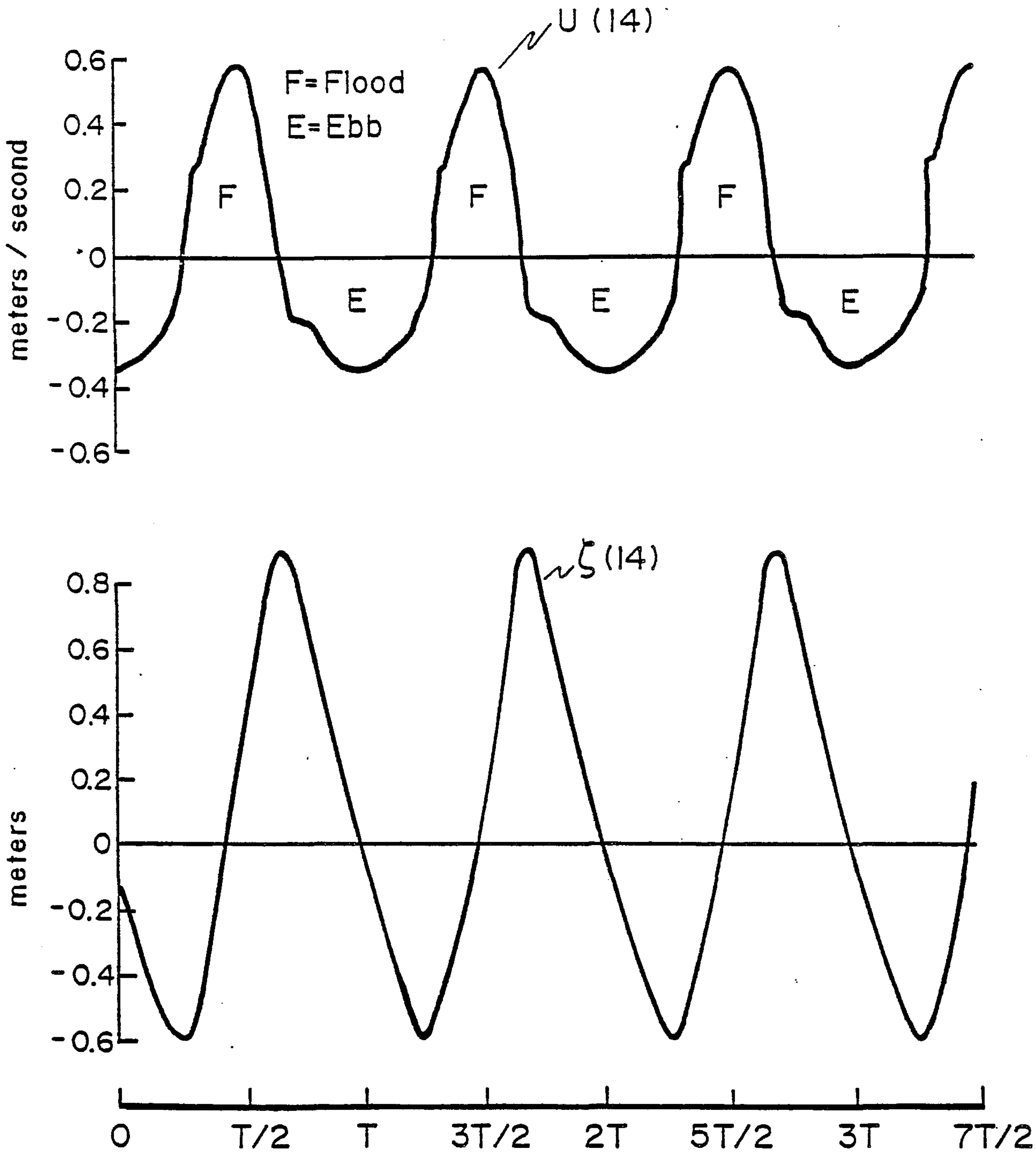

Figure 42. Predictions of near-surface velocity and sea surface elevation for time period and location shown in Fig. 41. Calculations are from numerical model of tidal flows in this region. Dominant sources of asymmetries are friction and time-varying channel geometry.

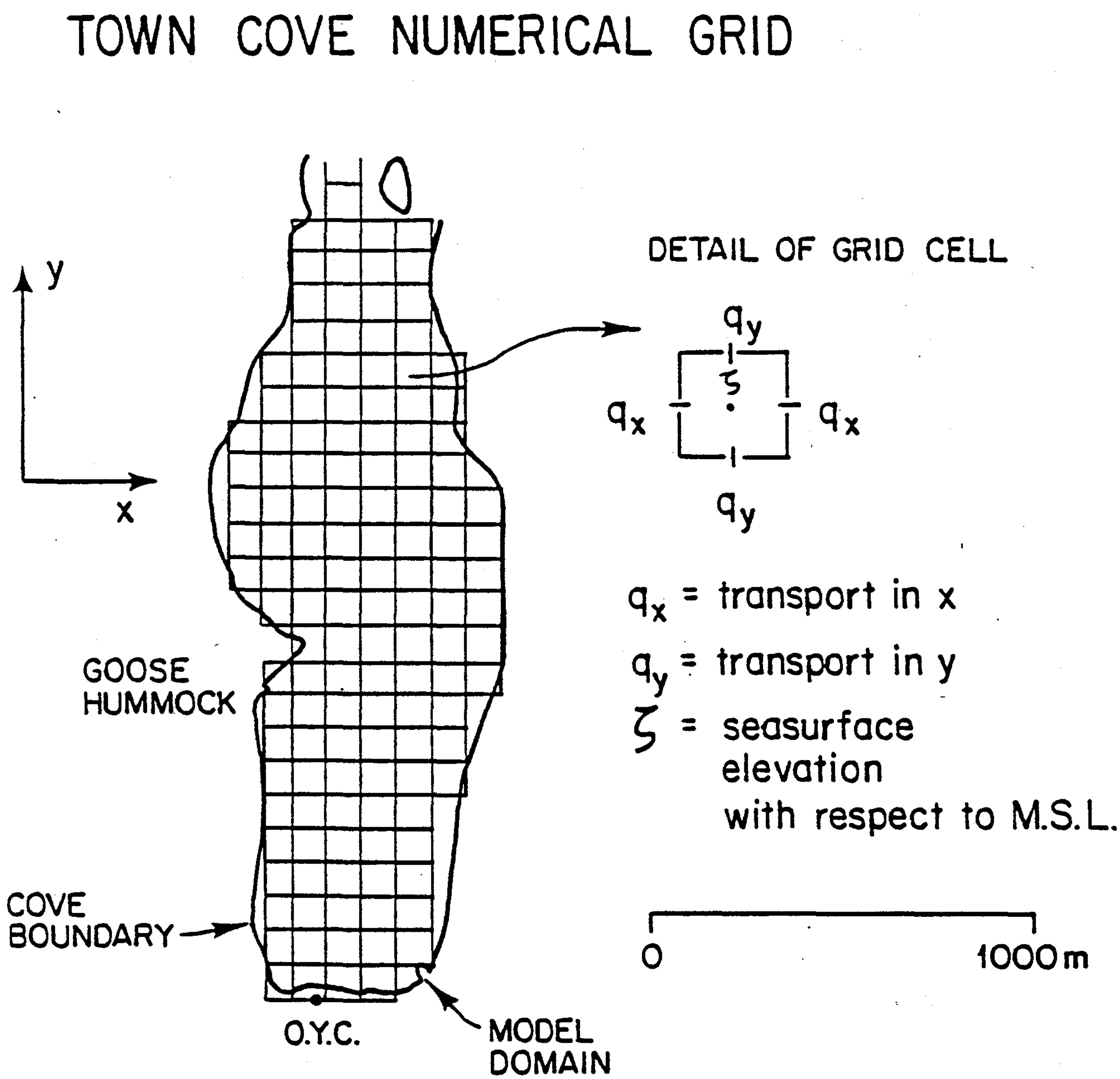

Figure 43. Schematic of grid used for two-dimensional computer model of Town Cove. Specific computational elements for a typical cell are shown in the inset. Time derivatives are approximated by forward time steps; spatial derivatives are calculated using centered differences.

A comparison of the tidal flux calculated using the two-dimensional model and the continuity model (described earlier) shows good agreement between the two techniques (Fig. 39). Because input to the numerical model must mirror the complexity of tidal processes, storm surge processes, and heating/cooling effects to properly generate results agreeing with measurements, we decided to use the continuity model generated from field data to calculate discharge past Mead's pier, rather than the more expensive, and data-critical, two-dimensional numerical model. The numerical model does, however, support the accuracy of the continuity model in estimating discharge. The continuity model has the added benefit of representing the actual water levels existing at the time of biological/chemical sampling, rather than water levels calculated from some representation of the physical forcing input into an approximate numerical representation of Town Cove physics.

C. Mixing Models

Models of mixing in Town Cove are essential for understanding nutrient exchange with the remainder of the ocean/inlet/estuary system. Nutrients introduced into Town Cove from ground water sources are exchanged through tidal action with surrounding waters. Nutrients and particulate matter from the estuary can also be exchanged or deposited within Town Cove. The mechanisms responsible for this mixing control the length of time a water parcel remains in the Cove (residence time), and subsequently the accumulation of nutrients in near-bottom waters, as well as the state of oxygenation of bottom waters. To achieve a better understanding of mixing processes, we combined theoretical arguments about mixing in bodies of water such as Town Cove with field measurements to evaluate the consistency of the arguments.

A key concept exerting control over mixing within Town Cove is density stratification, the presence or absence of vertical density gradients in a water column, with denser water below and lighter water above. For example, a cold, saline body of water might underlie a fresher, warmer body of water. Stratification inhibits mixing processes within the water column, hindering exchange of nutrients, oxygen, and other properties. Stratification determines where incoming tidal waters will mix; if stratification is strong, mixing may take place only near the surface of the Cove waters leaving the bottom waters stagnant (providing incoming water density is comparable with surface water density).

Mixing is also dependent on the momentum of the incoming tidal water or fresh water into the Cove. In the case of fresh water entering the Cove from the intertidal shoreline, velocities are low so mixing through momentum does not take place. However, since tidal water entering through the feeder channel from Mead's Pier into Town Cove has an appreciable velocity (up to approximately 1 m/sec), the momentum of this inflow may have a significant effect on mixing. Our mixing arguments therefore are based on the model shown in Fig. 44. Tidal water enters Town Cove as a jet on flood tide, mixing through momentum exchanges in the plunge zone which extends from the inflow location to the plunge line. At the plunge line, momentum effects become secondary to density effects (although entrainment or mixing with adjacent waters still continues). If the inflow is less dense than the Cove water, the inflow will exchange with surface Cove waters only. If the inflow is more dense than Cove water, the inflow will intrude into the denser, deeper water of the Cove, continually mixing with the ambient water it passes. This

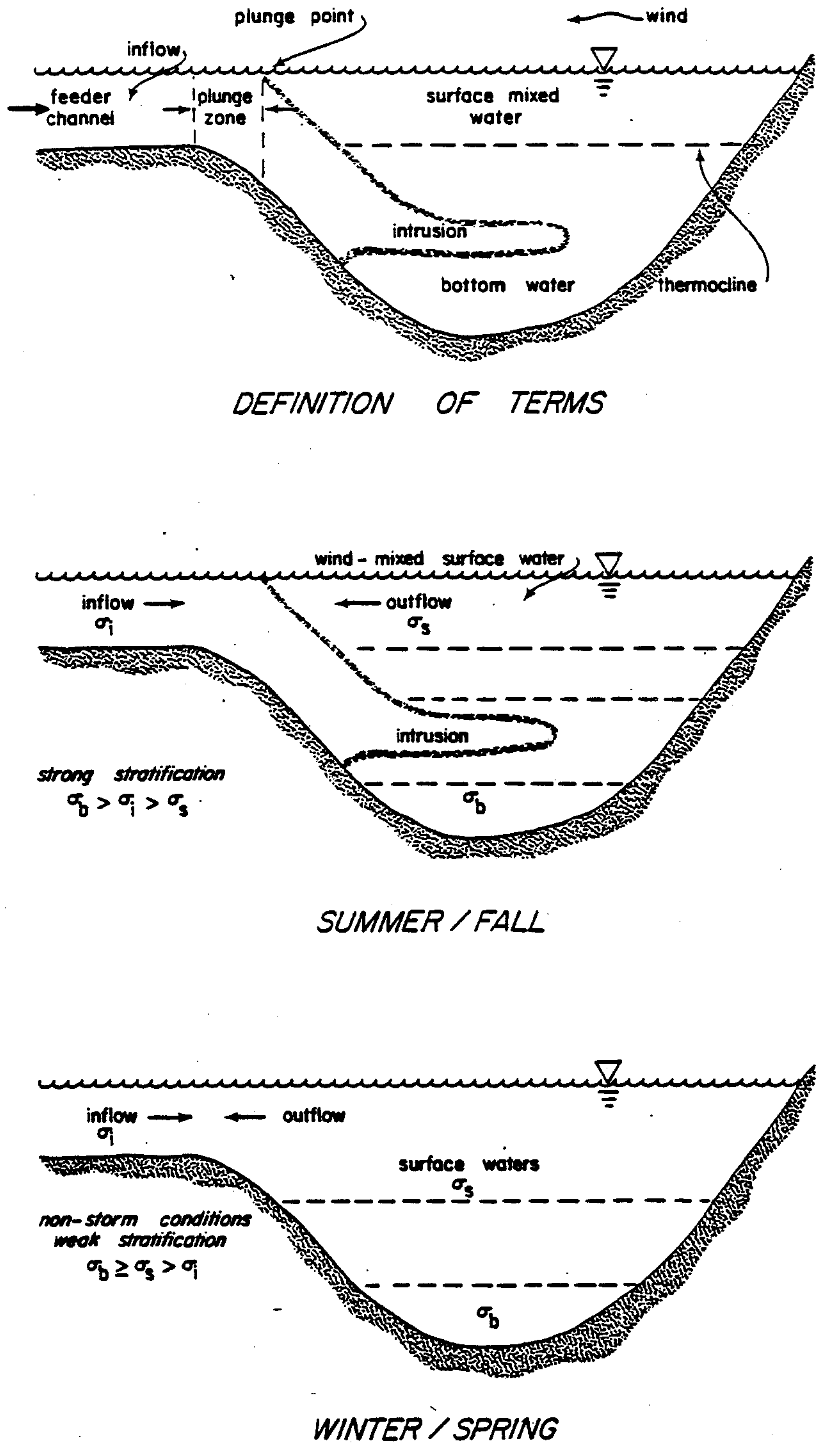

Figure 44. (Top Panel) Definition sketch for mixing terms; (center panel) schematic of summer/fall tidal mixing in Town Cove; (bottom panel) schematic of winter/spring tidal mixing in Town Cove.

continues until the mixed inflow reaches the density level (isopycnal) which is equal to that of the inflow, at which point the inflow will intrude along the isopycnal, with a general horizontal dispersion from there on. Because the denser inflow continually mixes with less dense water as it move towards its intruding isopycnal, the density level at which it intrudes will be lower than the initial density of the inflow. Tidal outflow behaves differently, however, with the outflow derived primarily from the Cove surface waters, including most fresh water inflow if the fresh water inflow is relatively warm.

Two examples are presented to clarify the arguments. First, assume tidal inflow is denser than surface Cove waters. As the inflow reaches the Cove, entrainment begins and the inflow plunges below the surface near the plunge line. The inflow plunges until it reaches its level of equal density, at which point it intrudes nearly horizontally. If the inflow density is greater than bottom water density, the inflow will intrude along the bottom of the Cove, renewing the Cove bottom water. On ebb tide, the outflow will be taken from surface waters, providing an efficient means of ventilating the Cove water: renewal on the bottom, extraction from the surface. Residence times in this case would be one to two days.

The second example is for an inflow which is less dense than surface Cove waters. In this case, mixing is mostly through momentum exchange processes, with no plunging of inflow below the surface. Inflow mixes only with surface waters, and outflow on ebb tide is derived from this same inflow (mixed slightly with ambient waters). Residence time for bottom waters in this case is much greater than one to two days, and is related more to storm-related mixing events than to tidal exchanges. Since storm frequency in this area is on the order of seven days, the residence time for bottom waters is closer to one week, during which time bottom water might become anoxic.

To investigate these mixing processes within Town Cove, we initially attempted to modify our two-dimensional numerical model to incorporate conservation equations for passive and active tracers. Verification of such a model, however, would involve a much larger field experiment than possible on the budget allotted, so we did not proceed far with the model. Concentration exchanges in such models are complex, and vertical density structure is important, leaving one with the choice of a three-dimensional model or a width-averaged two-dimensional model. As a brief look at the equations indicate, verification is a costly, and difficult, task; we opted to use the more descriptive mixing models discussed above, and conduct some simple experiments to investigate the seasonal variability in mixing. If, in the future, a more complete model and verification effort appears necessary, a careful dye-tracer study would provide a useful field methodology.

The importance of momentum mixing processes associated with the jet-like tidal inflow was estimated by calculating the distance to the plunge point for discharges and density profiles characteristic of Town Cove. Using mathematical descriptions of jet behavior formulated for stratified reservoirs (Fischer et al., 1979), we calculated this initial jet mixing to be small, confined to an area within one hundred meters from the point where the inflow discharge occurs. Although mixing is rapid in the area within the plunge point, it is not efficient in mixing the entire Cove. Thus density effects must account for any tidal mixing occurring within the Cove.

Field results from four sampling periods distributed throughout the year (Table 25), acquired by Goldman, Giblin and Gaines, provided measurements of

Table 25. Density of water at deep reference station (top and bottom) and at channel entrance to Town Cove (σ_T units).

		DEEP STATION	
	INFLOW	TOP	BOTTOM
3-4 November 1982	22.74	22.74	22.86
26-27 April 1983	23.39-23.74	23.41	24.28
29-30 June 1983	21.85	19.3	22.03
18-19 August 1983	21.42	21.2	21.7

salinity and temperatures over periods exceeding 24 hours within Town Cove (throughout the water column), from which water densities could be calculated. Densities are shown in σ_T units, where

$$\sigma_T = 1000\ (\rho - 1)$$

The winter observation (3-4 November, 1982) shows a slight stratification between surface and bottom waters at the deepest location within Town Cove, which is our Cove reference station. Incoming water is the same temperature or slightly warmer than Cove surface waters, so most tidal exchange is restricted to the surface. In the spring period (26-27 April 1983), little stratification existed at the deep station, with inflowing water generally less dense than surface waters. This restricted tidal exchange primarily to the surface waters. In the first summer period (29-30 June 1983), the water column was well-stratified, with incoming water more dense than water at the 2 m depth at the deep reference station. In this case, mixing of inflow took place at greater depths, down to 3-4 meters according to the density profiles. This colder, denser inflowing water therefore ventilates a greater portion of the water column in the summer than occurred during the winter and spring periods. The final summer period (18-19 August 1983) showed a well-mixed water column, following a large storm a week earlier (Fig. 45). Incoming water was colder and slightly more saline than surface waters, so the inflow intruded to a couple of meters below the surface, again ventilating a larger portion of the Cove than in the spring or winter periods. Since the inflow did not reach the bottom-most waters of the deep reference station, these waters were not continually renewed on a tidal period.

Because short, 30-hour samples are not adequate to separate tidal mixing from other mixing processes, we deployed an array of temperature sensors

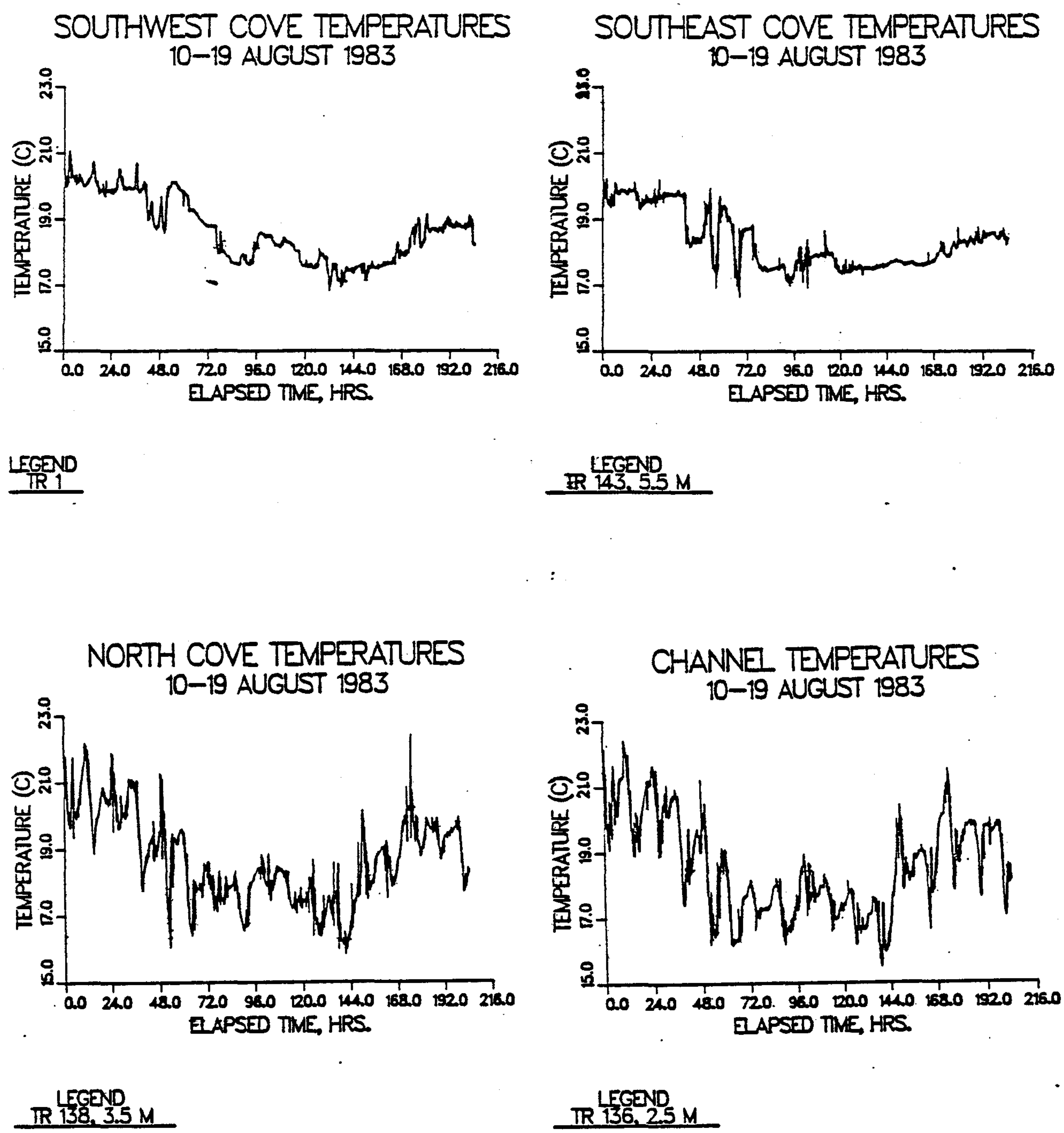

Figure 45. Temperature results from four temperature recorders over ten day period beginning noon, 10 August 1983, ending noon, 19 August 1983. Locations shown in Fig. 38.

throughout Town Cove along the bottom for a two-week period (Fig. 38). These temperature sensors (Sea Data Corporation Temperature Recorder-TR) sampled once every five minutes during this period, and were mounted approximately 20-30 cm off the bottom, at various water depths. Results (Fig. 45) indicate a major mixing event occurring shortly after the recording period began (Fig. 45 shows data from noon on 10 August through noon on 19 August), related to the passage of a severe storm on 12-13 August 1983. The storm completely stirred the entire Cove, removing all stratification for a few days following the event. The water column cooled several degrees centigrade, and gradually warmed up for the remainder of the sampling period. This mixing took place at the same time for all TR stations, and made the bottom waters nearly isothermal. Gradually, as warming occurred during the following days the water column became slightly stratified, as indicated by sampling during 18-19 August 1983. Overturning and renewal of the bottom waters in the summer therefore appears to be strongly controlled by storm events. Although there are strong tidal signatures in temperature at the channel station and north TR over the entire period of the study, there was no tidal signature at the deeper stations, lending support to the idea of predominant storm mixing even in summer months.

Field observations of salinity and temperature distribution support the following models of mixing in Town Cove. During the winter and spring months, when the Cove water is colder than inflowing tidal water, tidal mixing is confined to near-surface water in the Cove. Inflow remains near the surface, and outflow is also from the near-surface (Fig. 44). Complete mixing of the entire water column is related to storms, which occur frequently during winter months (Fig. 46). Residence time of surface waters therefore is on the order

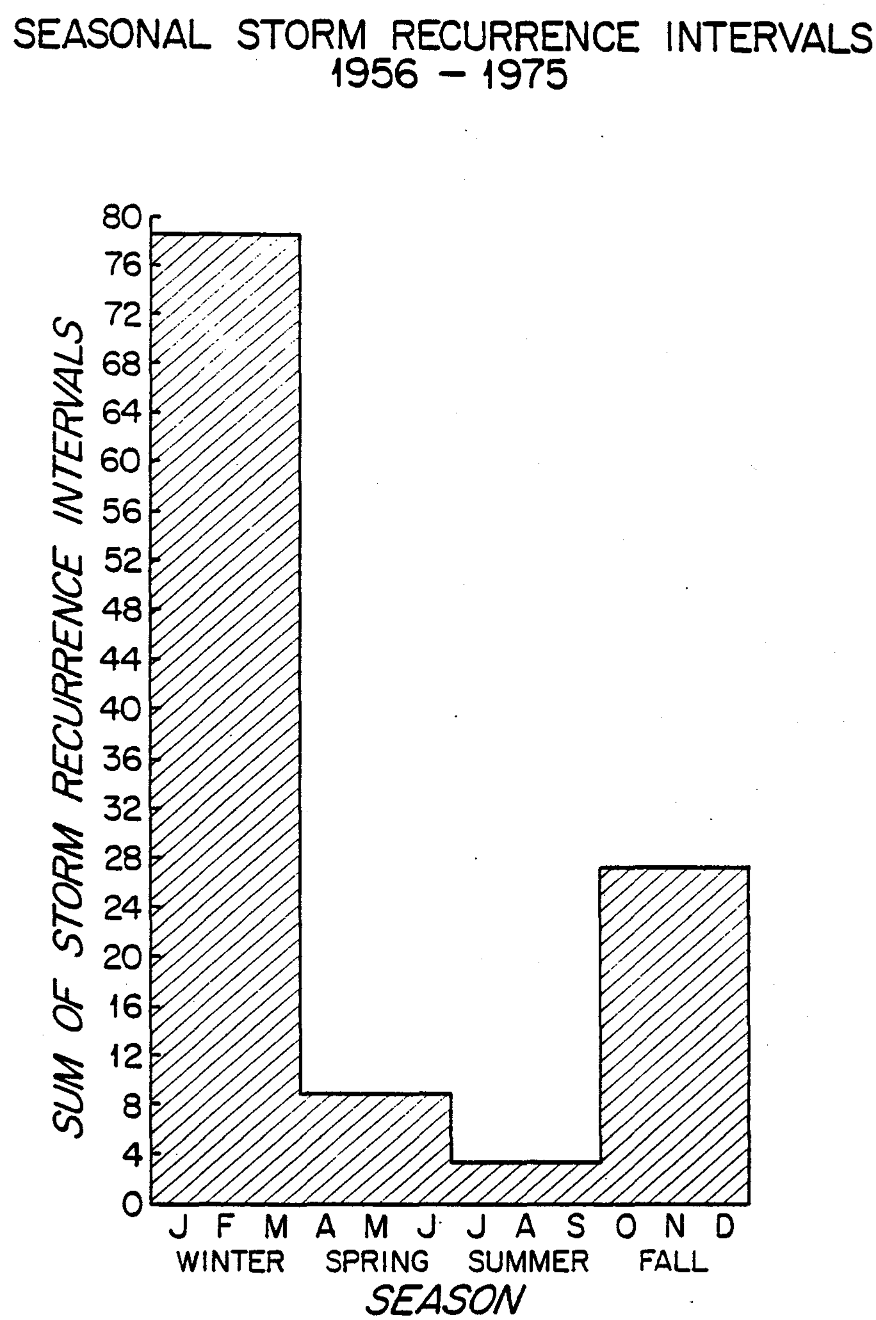

Figure 46. Seasonal storm activity as indicated by sum of storm recurrence intervals for period 1956-1975 for Cape Cod. Data from U.S. Army Corps of Engineer Compilation (from Speer et al., 1982).

of one day, while residence time of bottom waters is closer to one week, the approximate periodicity of storms in New England. Bottom waters may be anoxic for periods of days during spring when biological activity is increasing.

During the summer and fall months, incoming tidal waters are colder and generally more saline than water in Town Cove. This causes the inflow to plunge below the surface after a short period of intense mixing near the inflow point (Fig. 44). We have not documented a period where inflow was dense enough to mix with bottom waters in our deep reference station; the inflow generally mixes with intermediate depth water, ventilating the Cove water at that level and above. As our longer-term observations indicate, storms are responsible for thoroughly mixing most bottom water near the deep reference station. Minor mixing may still take place in deep waters during summer as colder, fresh groundwater flows into the periphery of the Cove, but this mixing is not nearly as vigorous as storm mixing.

These two models of mixing can be applied to dissolved nutrient species and oxygen exchange, but must be modified to account for the behavior of suspended particulate matter. Since suspended particulate material does not behave as passively as dissolved material, a model for particulate transport must consider its settling behavior through the water column. As much of the particulate organic material settles slowly through the water column, these mixing models provide a mechanism for suspended particulates imported into the Cove to be removed from that inflow and not be available for export on the following ebb tide. Observations of tidal behavior and consideration of processes responsible for transporting suspended particulate material suggest the following model. The strong flood tide asymmetry experienced in channels within Nauset estuary/embayment results in strong velocities during flood tide, and weaker velocities during ebb tide (Fig. 41). Since the ability to erode material from channel banks and bottoms is a function of the velocity (raised to some power greater than one), this velocity asymmetry results in more suspended material transported during flood tide than ebb tide. Channel scouring will be greater during flood tide. Consequently, as flood inflow enters Town Cove, the water is relatively high in suspended particulate content. As this water moves into the quiescent waters of Town Cove (where velocities are generally one-tenth or less of those in the feeder channels), suspended material settles out of the inflow. When the inflow density is greater than the Cove surface water density, the intruding inflow removes suspended particulate material even further from the outflowing surface waters. Outflowing water during ebb tide, then, has a lower suspended particulate concentration than inflowing water, resulting in a net accumulation of particulate material within Town Cove. Storms will mix some of this material into the Cove water column, but generally will not be vigorous enough to bring it to the surface for export from Town Cove. This peculiar trapping behavior within Town Cove is due to two effects which combine to make the process more efficient. First, the geometry of the Nauset estuary/embayment forces the tidal flow to have stronger flood flows than ebb flows (Aubrey and Speer, 1983a, b; Speer and Aubrey, 1983), a pattern not characteristic of all estuarine systems. Second, Town Cove provides a basin of relatively still water which allows suspended particulate material to settle out partially before ebb tide begins, enriching the Cove bottom in particulate material. Thus this behavior is not typical of all estuarine systems.

Net particulate fluxes past Mead's Pier will not necessarily reflect this net import to Town Cove proper. Net export of particulates to the estuary may result from the large areas of grasses between Town Cove and Mead's Pier. As an example, let's examine the effects of a large storm on particulate export or import. The storm likely will make available large amounts of particulate organic material for transport. During flood tides, this material will enter Town Cove, where a certain fraction will be trapped. On ebb tide, particulate material will be exported past Mead's Pier. Depending on the gross import of material past Mead's Pier from the estuary, the net transport past the pier may be seawards, even though Town Cove itself is a net sink. Presence of the tidal flats between Twon Cove and Mead's Pier therefore complicates interpretation of particulate flux estimates.

D. Freshwater Inflow

Fresh water inflow into Town Cove must be calculated by a variety of indirect means, since direct measurement is nearly impossible. Measurements of sea surface elevation and salinities at Mead's Pier provide three methods for estimating freshwater flow past this location. Although fresh water is entering Town Cove from its periphery, it is possible that fresh water could enter Town Cove from the estuary since freshwater is discharging into the entire Nauset estuary/embayment. Thus net flux of freshwater can be either into or out of Town Cove.

The first two techniques for estimating net freshwater inflow are based on simple water and salt conservation equations:

$$Q_o = Q_i + Q_R$$

$$Q_o S_o = Q_i \; S_i$$

where Q_o = volume of outflow past Mead's Pier

Q_i = volume of inflow past Mead's Pier

Q_R = residual volume, or balance between freshwater flow and evaporative losses.

S_o = salinity of outflow

S_i = salinity of inflow

These equations can be used to estimate the residual flow, Q_R, as follows:

$$Q_R = Q_o(1-S_o/S_i)$$

$$= -Q_i(1-S_i/S_o)$$

These equations pertain to the case where inflow and outflow represent different masses of water, and not directly to the case of inflow and outflow mixing alternately as the tide changes. However, the equations can be used to yield an upper bound on the amount of freshwater inflow (Table 26) and an estimate of the actual freshwater inflow (Table 27). First an upper bound can be estimated by assuming all inflow is at the highest observed salinity during flood tide, and the outflow is at the lowest observed salinity during outflow. Second, the approximate freshwater input can be estimated as the discharge resulting from use of the average salinity of the inflow and average salinity of the outflow. In all cases, the freshwater discharge (net) is less than 10% of the tidal flux, and probably less than 3%.

A third method for calculating flux is based on actual discharges and salinities for the time period of interest. Discharge is calculated from the continuity model (discussed previously), while salinity is measured from _in situ_ samples. We approximate the average salinity across the channel width and over the channel depth, as well as between measurement intervals, by a

Table 26. Estimates of net freshwater outflow from Town Cove determined from a salt balance using extreme flood and ebb salinities. $\bar{S}_E$ is maximum ebb salinity; $\bar{S}_F$ is maximum flood salinity. These estimates are upper limits on freshwater inflow based on a model not directly application to Town Cove. For more applicable estimates, see Tables 27 and 28.

	$1-\bar{S}_E/\bar{S}_F$	Q_{net}, m^3
13–14 March 1983	0.098	2.5×10^5
26–27 April 1983	0.051	1.3×10^5
29–30 June 1983	0.035	8.7×10^4
18–19 August 1983	0.034	8.5×10^4

Table 27 Estimates of net freshwater outflow from Town Cove from salt balances using average flood and ebb salinities. $\bar{S}_e$ is the average ebb salinity, while $\bar{S}_f$ is the average flood salinity. These estimates of net outflow are in close agreement with those calculated using an independent measure of freshwater inflow, Table 28.

	$1-\bar{S}_E/\bar{S}_F$	Q_{net}, m^3
13-14 March 1983	0.027	6.8×10^4
29-30 June 1983	0.011	2.8×10^4
18-19 August 1983	0.002	5.0×10^3

single measured value. This approximation has been made for certain nutrient calculations, as well. In general, point measurements of nutrients or salinity are not representative of time- and spatially-averaged quantities, particularly in a tidal inlet where these nutrient and salinity flux calculations are generally applied. In inlets, large temperature and salinity differences between the ocean and estuary result in considerable non-homogeneity in flow characteristics and nutrient distributions. Considerable vertical and lateral gradients in concentration can be expected in such situations. For the present case, however, since the flow measurement section is midway along a considerable length of tidal channel where turbulence levels are high and water depths are shallow, the water properties are well-mixed by the time they reach our measurement point. Therefore dissolved species can be expected to be less variable in concentration than in a tidal inlet, although some variation certainly exists. We argue that this variability is less than the signal we are trying to measure, an argument supported by the observation of a strong tidal signature in many nutrient measurements. The proper procedure would have been to test this argument of homogeneity, which we did not do properly.

Particulate material, however, does not obey such an assumption of vertical mixing. Because particulates are not totally passive they have a concentration gradient, with larger concentrations near the bottom. A point sample by itself therefore will not necessarily be representative of mean conditions. This is complicated further by the fact that the suspended particulate distribution will change with changing flow structure, so estimates of particulate flux will have large errors associated with them.

However, if particulate concentrations show a strong tidal signature then the trends are likely correct, if not the absolute numbers.

Results for salinity balances using this continuity technique show freshwater outflow for two periods (Table 28), with an average value of approximately $5x10^4$ m^3 per 24-hour period. The third period showed an insignificant net influx of freshwater.

Although all flux calculations were made for a diurnal tidal cycle (approximately 24.8 hours), the large number of time scales associated with tidal processes make it difficult to conserve volumes of water over a single 24.8 hour period. Storms and similar transient disturbances also can greatly alter the net discharge of water (and hence dissolved and suspended material) over a 24-hour period. As an example, during an intense storm on 9 October 1982 (Fig. 47), water level in Town Cove was approximately 0.7 m above normal tide levels (Fig. 48), which accounts for a volume of about one-half that exchanged on a normal tide. Because of this increased volume within Town Cove, estimates of net discharge over 24-hour periods during the storm would show a large net loss or gain, depending on whether the sampling took place during the rise in superelevation, or during the decline. This variability in sea levels over short periods of time make 24-hour observations of nutrient exchange susceptible to large errors. To account for these errors, we have calculated net discharge over the sample interval, and multiplied that by a mean concentration to obtain the bias in our flux estimates due to pure advection of more material on flood or ebb tide:

$$\Delta C = \bar{C}\Delta Q$$

Table 28 Estimates of freshwater influx to Town Cove based on a flux salt balance calculated from hourly salinities and hourly water fluxes. S_{net} is the net salt flux, positive into the estuary, negative out. $S \Delta Q$ is the net advected salt from net water flux inequality. Q_R is net volume of freshwater entering Town Cove; plus is entering, negative is leaving. These values represent our best estimates for net freshwater inflow/outflor for Town Cove on the dates listed.

	(kg) S_{net}	(kg) $S \Delta Q$	(m^3) Q_R	
13-14 March 1983	8.42×10^6	6.42×10^6	-6.7×10^4	(out)
29-30 June 1983	-2.75×10^6	-4.15×10^6	-4.7×10^4	(out)
18-19 August 1983	1.34×10^6	1.38×10^6	$+1.3 \times 10^3$	(in)

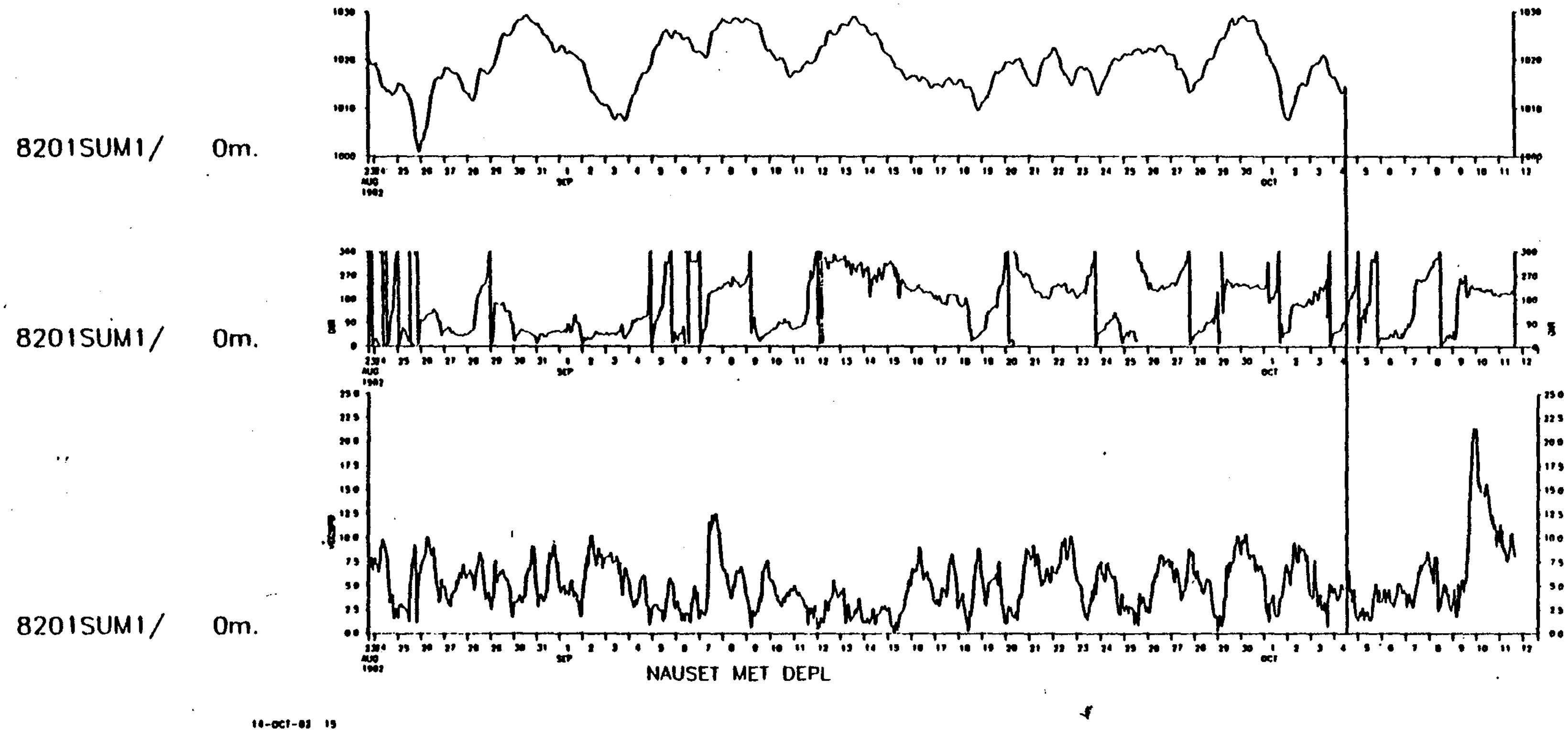

Figure 47. Meteorological-records (barometric pressure; wind direction, wind speed) documenting the October 9, 1982, storm at Orleans, Massachusetts.

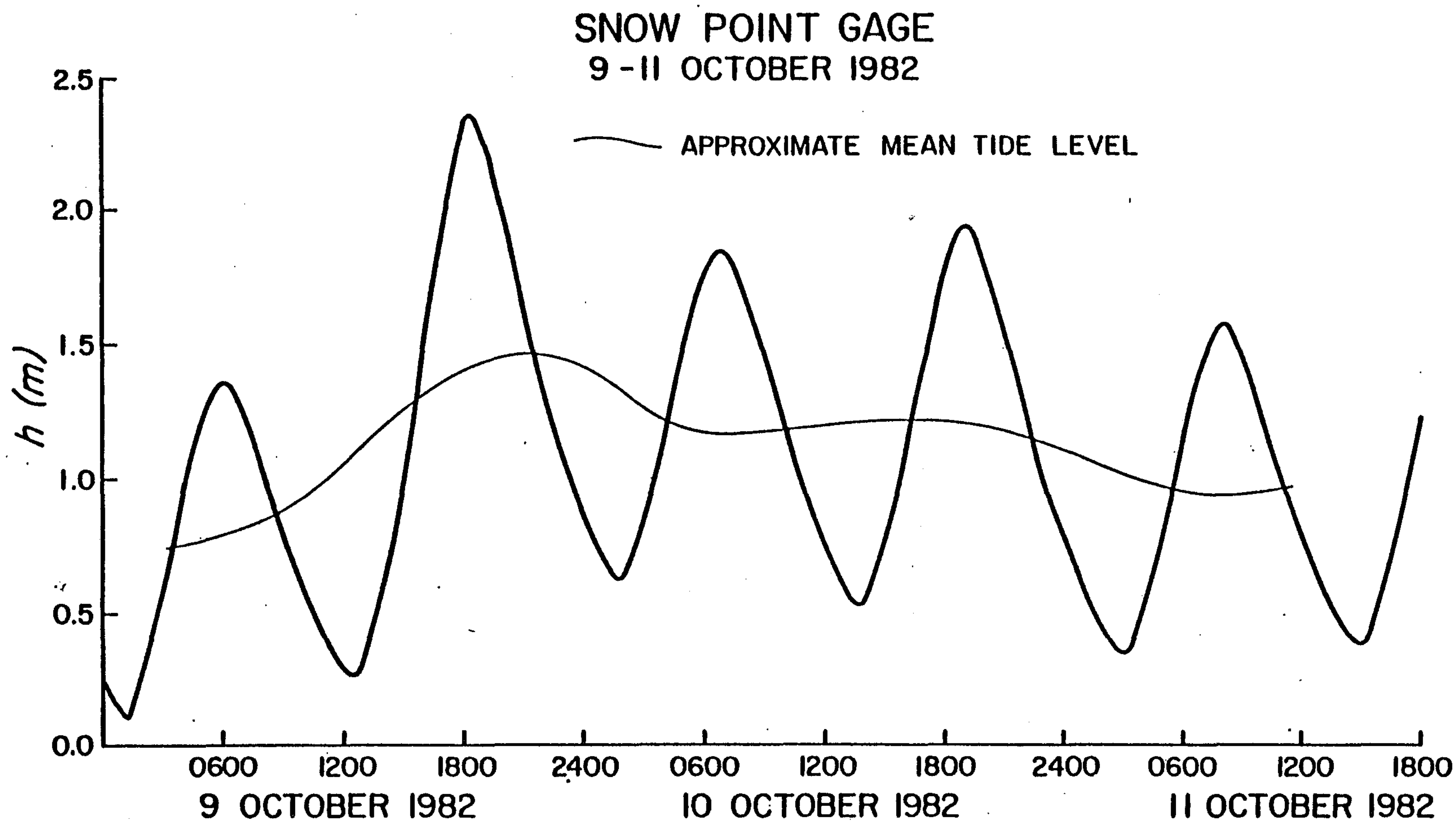

Figure 48. Tidal record for the Snow Point gage during a storm event. October 9 - 11, 1982. Town Cove, Orleans, Massachusetts.

This quantity must be used in interpretation of estimates of net flux of suspended particulate or dissolved material. In the above equation, C is the mean concentration of the material, while ΔQ is the residual flux calculated from the continuity model.

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Nitrogen budget of Town Cove

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Our purpose in this section is to present an overview of the nitrogen budget for Town Cove (Fig 49), drawing on other parts of the report as well as providing some new information. It should be pointed out at the start that these numbers are often subject to a wide range of uncertainty and are often reliant on numerous assumptions.

We have a number of estimates of nitrogen loading from groundwater input to Town Cove. Our best estimate of groundwater nitrogen loading into Town Cove is between 19 and 35 Kg. N/day, based largely upon the most likely discharge rate of freshwater into Town Cove. From the steady state model for recharge combined with measured nitrate concentrations in water entering Town Cove or observed in wells near its shore, (Table 4) we get a loading value of 19 Kg N/day, if 1982-83 recharge was 18 inches and assuming steady state. Discharge based on measurements of seepage resulted in higher values for loading, 68-80 Kg N/day (Table 6), but as mentioned earlier these measurements were taken during a period of likely high groundwater flow and our assumption regarding the discharge area may be high, as well.

Using an independent method based on statistics of anthropogenic nitrogen flux and the distribution of residential and commercial establishments in Orleans, Pelsit (CCPEDC, 1983) estimates nitrogen loading for the Town Cove recharge area at 31 to 33 Kg N/day of which about 9 comes from fertilizer and 24 is sewage-derived nitrogen. Of the total groundwater nitrogen input to Town Cove, Pelsit estimates 24% to 34% comes from the town center core area proposed for sewering. Our independent estimate from groundwater

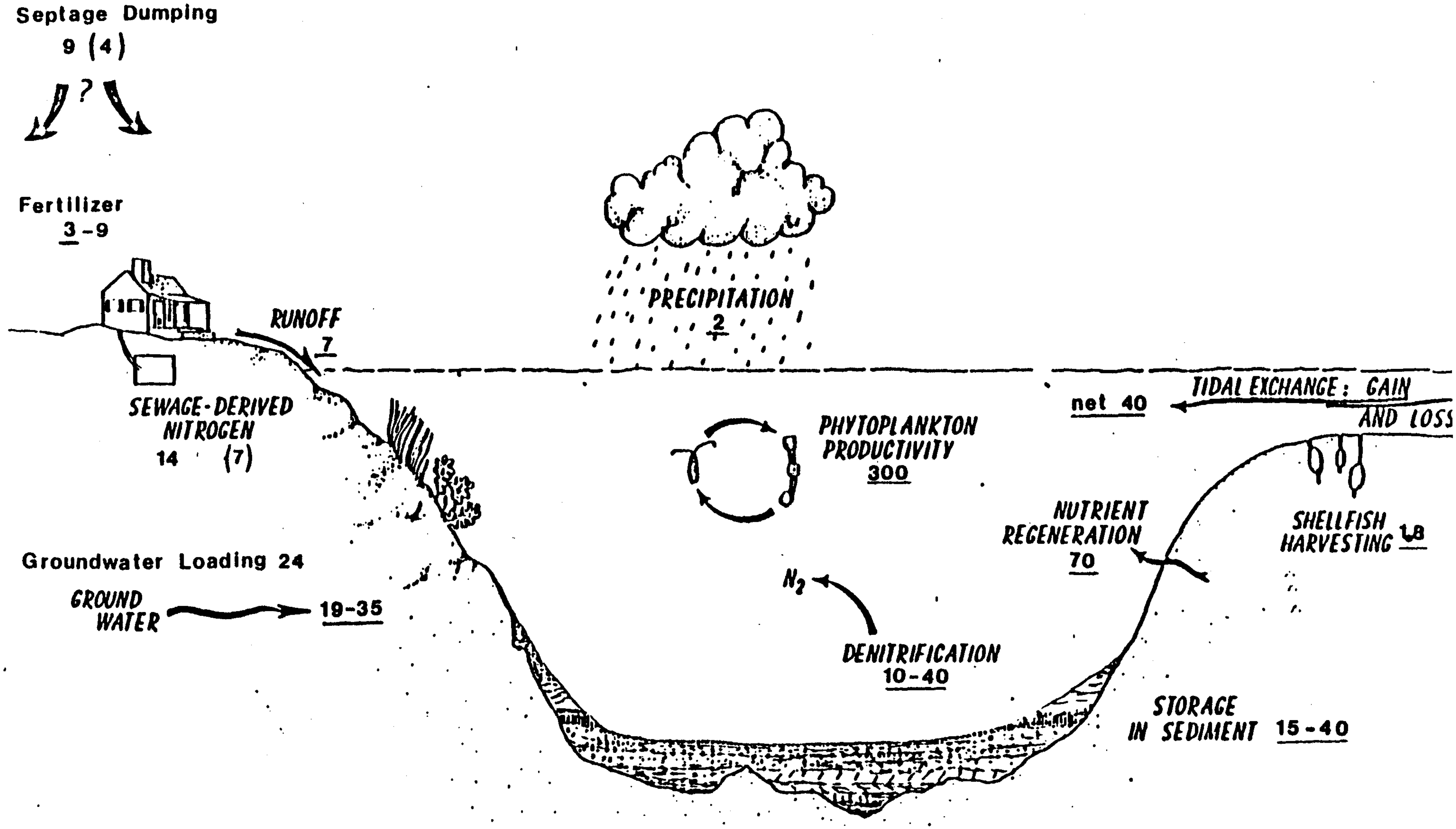

Figure 49. A Nitrogen Budget for Town Cove, Orleans Quadrangle, Mass. Values i. kilograms nitrogen per day. Values in parentheses apply to the Town center area. Underlined valued were determined substantially by this report.

nitrate measurements and relative discharge estimates is a maximum of 45%, of which unknown portions might be coming from sources such as the old landfill or the present landfill.

From landfill septage dumping data of Metcalf and Eddy (1983), and using a nitrogen content for septage of 150 ppm, we calculate the landfill receives up to 9.0 Kg N/day in total, of which about 4 Kg N/day comes from the Town center area. Because of the uncertainty in the direction taken by the landfill effluent, mentioned earlier, it is not known whether this septic-derived nitrogen eventually enters Town Cove, as indicated by LEA, or moves toward Crystal Lake, as indicated by Schofield Brothers. In any case, it can be treated as a separate pathway. We do not have an estimate on the nitrogen loading of groundwater by the existing landfill, or the former one located closer to the Cove.

Nitrogen loading from the operation of septic systems was estimated using information from outside sources. From statistics of domestic and commercial nitrogen use, given by Belfit (1983), nitrogen loading of groundwater from septic systems is approximately 14 kg N/day for the entire recharge area and about 7 Kg N/day for the core area proposed for sewering, taking into account that some septage nitrogen is brought to the landfill (where its ultimate fate is unknown). An independent approach, using water consumption data in Metcalf and Eddy (1983) and the assumption that nitrogen-free water from the municipal system enters the groundwater with 15 to 60 ppm of nitrogen indicates a range of septic nitrogen loading values for the core area of 2 to 15 Kg N/day, adjusting for removal of septage.

Our estimate of nitrogen input from lawn fertilizer is based on sales at two large hardward stores in Orleans. In one case an average of 4.0 Kg N/day has been sold over the past four years (3.5 Kg N/day in 1982). A second hardware store estimated a minimum of 3.0 Kg N/day in 1982. We assumed the third major hardware store sold the same amount and that commercial landscape companies and other fertilizer sources provided an equal input; based on discussions with the store managers, we assumed 25% of this fertilizer could have been used in the Town Cove recharge area and watershed, a total of up to 3.3 Kg N/day loading to Town Cove. An independent estimate of fertilizer input by Pelsit (1983) based on EPA statistics for average domestic fertilizer use, gives the total input to Town Cove from this source as about 9.6 Kg N/day. From discussions with residents of Orleans we feel our lower number is probably more reasonable.

Nitrogen input from precipitation for rain falling directly on the surface of Town Cove was estimated using data from a rain collection station located in South Truro and the amount of precipitation from September 1982 - August 1983. As mentioned before, this was an unusually wet period and 63.3 inches of rain fell (the average for rainfall between 1951 and 1980 was 46.8 ins.). The volume weighted average of inorganic nitrogen concentrations was 0.217 ppm. This concentration is almost identical to nitrogen concentrations measured at Falmouth in the late 1970s so we doubt that there is a large local variation. We calculate the inorganic nitrogen input from rain was about 2 Kg N/day, or higher if dissolved organic nitrogen forms in precipitation are included.

Run-off entering Town Cove has been estimated earlier to carry about 2 to 7 Kg N/day to Town Cove, averaged over a year. From our measured values of nitrogen in storm water, the loading from run-off is somewhat lower here than for other areas of Cape Cod.

Our measurements of nitrogen content and discharge from Gutter Pond near the Town Hatchery, yield an estimate of nitrogen added from this source. During dry periods, when discharge is largely from groundwater, discharge from Gutter Pond adds about 0.8 Kg N/day to Town Cove.

Using the estimates of Goldman and Dennett, reported earlier in this report, it appears net tidal influx of nitrogen, mainly in the particulate form, is a large term in the nitrogen budget of Town Cove. Individual determinations of this value vary widely, but 40 Kg N/day appears to be a representative value. Possible reasons for the large magnitude of this term are discussed by Goldman and Dennett, and by Aubrey and Speer, elsewhere in this report. It should be emphasized that the net flux of tidal nitrogen is small compared with the flow in and out, which Goldman and Dennett estimated to often exceed 150 Kg N/tide.

Our estimations of denitrification in Town Cove suggest large quantities of nitrogen are not lost from groundwater by this process as it discharges through the estuarine sediment. However, denitrification at other sites, such as the anoxic sediments or water that periodically occur in deep portions of Town Cove appears likely. Based on rates reported by other studies, we estimate this term could be as large as 10 to 40 Kg N/day in Town Cove.

On the basis of considerations discussed by Giblin, elsewhere in this report, we believe from 15 to 40 Kg N/day are buried in the sediments of Town Cove as particles settle out of the water column.

Certain biological processes recycle nitrogen within the Cove, but do not consititute a net gain or loss. Release of nitrogen from organic sediment in the Cove was determined to be about 70 Kg N/day by Giblin, based on her field measurements. All of this could be compensated for by sedimentation and uptake by aquatic grasses and phytoplankton, which are also believed to have rapid recycling rates. For example, a productivity of 50ug C/1/hr reported by Goldman and Dennett in this report, could be associated with nitrogen uptake equivalent to nearly 300 Kg N/day in Town Cove. A typical value for the standing crop of particulate nitrogen reported by Goldman and Dennett, 19 ug N/l in Town Cove, could amount to a total standing crop of 57 Kg N.

We obtained shellfish harvest figures from Orleans and Eastham shellfish officers (Libby-MacFarlane, personal communication; Lind, personal communication), including separate estimates for inside versus outside the Cove. This includes shellfish taken from grants inside the Cove. Using data from "Fisheries Statistic of the US" and data for nitrogen content of shellfish meats, (Ansell 1965, Ansell 1974, Giese 1969) we estimate 1.8 Kg N/day in 1982 was harvested from Town Cove. This represents a net loss only if the shellfish were consumed outside of the recharge area. It should also be pointed out that the harvest of mussels (*Mytilus edulis*) in the outer Nauset embayment in Orleans is many times larger. We did not take this into account in this budget, but it illustrates shellfish harvesting could become a significant term.

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PART THREE - NAMSKAKET MARSH

The Potential Impact of the Proposed Disposal Area on Namskaket Marsh

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Description of the Wetland

The area designated for construction of a proposed septage and/or septage-sewage treatment plant, "area 4" (LEA, 1981b), is north of the Orleans Town Highway Department garage, at the landward end of Namskaket Marsh (Fig. 50). The wetland expected to receive the effluent is known as "Hurley's Bog" (Orleans Assessor's Map) and is of 4 to 5 acres (16,000 to 20,000 m^2) extent (depending on which map one uses), of which most lies within the site boundary. Members of our staff visited the area on three occasions: July 9, July 15 and October 15, 1982.

Hurley's Bog is one of two small lobes of Namskaket Marsh that were separated from the main body of the marsh by the construction of a railroad embankment (now a bicycle path) in the late nineteenth century. Restricted flow of water between these areas and the main marsh occurs through a single culvert under the embankment for each lobe. Hurley's Bog is at present a fairly typical, moderately dry freshwater marsh, showing influences of seawater flooding along the ditches that cross its surface. The edges of the marsh are occupied by a combination of reed (<u>Phragmites</u>) and cattail (<u>Typha</u>), along with some of the shrubs characteristic of such environments, like red maple and sweet pepper bush. In the center of the marsh, where the seawater influence is more apparent, there is "three-square grass" (<u>Scirpus</u>), black rush (<u>Juncus</u>) and traces of spike grass (<u>Distichlis</u>) and of <u>Spartina</u> <u>patens</u>. The most conspicuous indication of the influence of brackish water is marsh

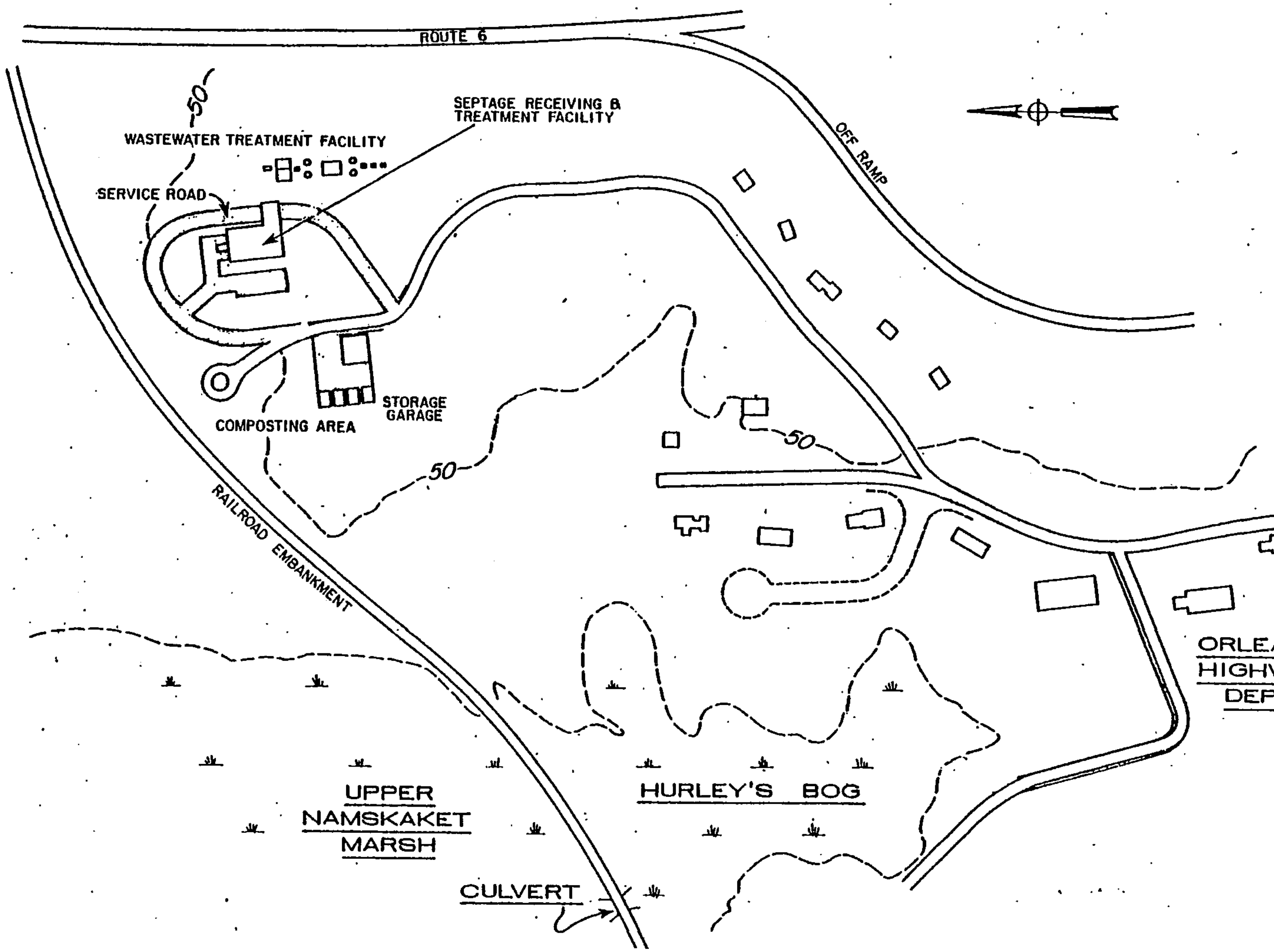

Figure 50. Site 4, the location of the proposed septage or septage/sewage treatment plant adjacent to Hurley's Bog and Namskaket Marsh, Orleans, Massachusetts. Recent changes in the site plan are not shown.

elder (Iva frutescens). The tide range in ditches in Hurley's Bog appears to be 30 to 50 cm. During one visit, water was coming underneath the railroad embankment through what appears to be a wooden culvert about 18" in diameter; the water had a salinity of about 4 o/oo; the water level in the outer salt marsh at the time had not quite reached the level of the marsh top. On another occasion water ebbing from this wetland ditch was fresh.

Namskaket Marsh has an area of about 232 acres (9.39×10^5 m^2). The upper reaches of Namskaket Marsh, west of the railroad embankment, show strong influence of fresh water, although to a lesser degree than Hurley's Bog. The plants around the border of the marsh include Spartina, but Typha mixed with marsh mallow, three-square grass and reed predominate. Along the creek banks there is very vigorous growth of reed (Phragmites). Spartina alternaflora occurs along the edges of the creek banks and in certain places is mixed with Phragmites. Spartina patens, the predominate plant of this genus, occurs in relatively small and isolated patches which look quite healthy. Water in the ditch along the railroad embankment had a salinity of 6 o/oo in October 1982.

There is a very large amount of wrack and debris in this portion of Namskaket Marsh, evident throughout the summer. Deposits are sufficiently heavy that large areas of vegetation on the marsh table have been smothered. On one visit it looked as though a recent high tide had moved a lot of the wrack leaving bare mud exposed. Elsewhere in upper Namskaket Marsh we observed a typical marsh panne, devoid of grasses, containing brackish water (8 o/oo) and smelling of sulfide. It is impossible to say from a few visits whether the marsh is changing; but it is obvious that it is a transition area, a brackish marsh, somewhere between being a fresh water and a salt water marsh.

Impact of the Proposed Effluent

Based on our experience and familiarity with the literature on this and related topics, marshes and wetlands can be said to have a large capacity to take up nutrients, such as nitrogen, compared, for example, with natural bodies of water. Freshwater swamps with standing water have been used throughout the world for removing nutrients from sewage and there is an appreciable literature dealing with this topic. In our opinion, the combination of fresh and salt water wetlands present at the proposed site offers an opportunity to make probably the best possible use of wetlands in a sewage effluent treatment system.

Potential impacts on Hurley's Bog and Namskaket Marsh can be categorized as a) effects of fresh water, b) effects of nutrient loading, and, c) effects of pollutants (e.g., toxins). To some extent, all three categories of impact depend not only on quantities of leachate and nutrients involved but also on how the effluent enters the marsh system. The concept of "marsh engineering" ought to be considered in the event control of the delivery, distribution and/or standing level of effluent in the wetland becomes desirable.

According to LEA (Weisman, 1983):

a) Leachate from the sewage treatment facility is not expected to break out onto the slope between the recharge beds and Hurley's Bog (as suggested in an earlier analysis; cf. LEA 1981b);

b) Leachate is not expected to pass under the wetland into Cape Cod Bay;

c) Leachate is expected to enter the fresh and saltwater wetland system. "The best available information showing direction and width of the leachate plume is contained in Part II, Section II-B of our facilities plan, Fig. 7. This figure indicates that most of the leachate will discharge to the freshwater wetland. It would be necessary to develop and execute field studies and detailed analysis beyond the scope of our current design in order to define more precise estimates of the leachate fraction discharging to the freshwater wetland."

Our discussion of impacts of the leachate may be invalidated in part if the path or quantity of leachate were significantly different from that described by LEA.

A. Fresh Water

Effluent volumes estimated for the proposed septage treatment plant range from 16,000 to 77,000 gallons per day, depending on the season and day of the week, but on average are between about 16,000 and 35,000 gallons per day. Flows from a combined septage/sewage plant would vary from 99,000 to 1,780,000 gallons per day, depending upon the above factors as well as the phase of sewering and extent of hook up of developable lots in the service area (Weisman, 1983). On average days these predicted flows narrow to from 88,000 to 272,000. In comparison, according to figures of Metcalf and Eddy (1983), current water use in the core area is about 85,000 gallons per day. If freshwater discharge to the Namskaket Marsh system is similar to that of Town Cove, natural discharge would be about 2,000,000 gallons per day.

If the effluent primarily enters the ditch or creek system of Hurley's Bog and exits directly via the culvert, the bog soils and vegetation may have only limited exposure; both the impact and the opportunity for removal of nutrients would be low. Greater exposure may occur naturally, or could be encouraged by controlling the water level in Hurley's Bog (according to LEA, this is not planned at present). With more exposure, it might be expected that the wetland community would change toward an assemblage of species more typical of the standing water swamp, characterized by the cattail, Typha, and the reed. This change could be immediately obvious and would result in loss of the low grasses and Iva. This area also might then become more attractive to forms of wildlife such as muskrats. As mentioned above, freshwater swamps with standing water have been used throughout the world for removing nutrients from sewage; in terms of impact, however, a decision would need to be made whether the floristic change and associated responses are acceptable.

Freshwater leaving Hurley's Bog would also be expected to affect adjacent areas of Namskaket Marsh, increasing the cattail and reed marsh portion and diminishing the present salt marsh plant component. That would mean the grasses would be taller, attract different wildlife and present a different scenic aspect. It would not necessarily be accurate to imply the area becoming a more brackish marsh constitutes a degradation, but it would definitely be a change.

B. Nitrogen

The consequences of putting moderate amounts of nutrient rich freshwater into the fresh water swamp would be to enrich the area and enhance its productivity. Under the wastewater/septage plan LEA projects that the concentration of nitrogen (primarly ammonia) reaching the recharge beds will be 25-30 mg/l (Weisman, 1983), a range that appears reasonable. Typical wastewater contains 15-60 mg/l nitrogen and about 25% of this is removed by treatment as sludge. Under the septage-only plan LEA projects that the nitrogen concentration will be 75 mg/l and again we feel that this is a reasonable assumption.

The indicated concentration of total nitrogen reaching the wetlands is 0-10 mg/l nitrogen in the wastewater/septage plan and 0-15 mg/l in the septage-only plan. There are only three ways in which nitrogen can be apparently lost between the recharge beds and the wetlands: 1) dilution by groundwater low in nitrate, 2) adsorption of ammonia by the soil, and, 3) denitrification. We will address these three mechanisms because we do not think the loss of nitrogen will be as large as indicated above.

1) Dilution - this will only change the concentration of nitrogen in the groundwater; it will not change the overall loading of nitrogen to the wetland. It does not represent a real loss of nitrogen.

2) Adsorption - Initially, there could be some adsorption of ammonia onto soil particles. Soil has a limited capacity for adsorption, and in sandy soils this capacity is quite low. We have calculated the nitrogen loading, assuming in the steady state there is no loss by this process.

3) Denitrification - Denitrification represents a real loss of nitrogen and unlike adsorption it could continue throughout the life of the treatment plant. From the evidence presented to us, and from information we have gathered on rapid infiltration, however, we find no evidence that there will be a large loss of nitrogen by this process in the leaching beds. Our conclusion is based upon several factors:

a) Denitrification requires two steps: first, ammonia must be oxidized to nitrate. This process requires oxygen and occurs in well drained sands. Second, nitrate must be denitrified to N_2 gas. This process occurs in the absence of oxygen, usually in waterlogged soils. Achieving efficient denitrification requires that leaching beds are managed on an alternating scheme of wastewater loading and drying. Optimum rates can only be achieved after studying local soil conditions and by careful management. LEA has not proposed any scheme to manage the beds in this manner, although this could be considered.

b) Both steps, nitrification and denitrification, have temperature and pH requirements (EPA, 19**). Rates are exceedingly low at pH's below 5.5 and temperatures below 5°C. We have no data on the pH of these soils, but for a significant portion of the year the temperature will be below 5°C.

Denitrification requires carbon. Approximately 2 mg/l total organic carbon is required to denitrify 1 mg/l nitrogen (EPA design manual). For this reason it is difficult to achieve denitrification in secondarily treated effluent since the organic carbon content is low. If the BOD_5 in the effluent is approximately 30 mg/l and we assume an oxygen to carbon ratio of 1, then there is only enough carbon present to denitrify 15 mg/l of nitrogen under optimum conditions.

For these reasons we do not expect much nitrogen removal in the leaching beds. As a result, we have made our calculations on the impact of nitrogen on the wetlands assuming no nitrogen removal. It does appear to us that there is potential for achieving some nitrogen loss in the beds by regulating the application rates and possibly by supplementing carbon. The costs and benefits of this would have to be considered.

Hurley's Bog is approximately 5 acres in area (20,000 m^2). Under the sewage/septage plan if 272,000 gal/day ("future summer average") is discharged to the leaching beds and we assume there is no nitrogen removal in the beds (N content = 30 mg/l) the nitrogen loading to Hurley's Bog would be 1.5 g $N/m^2/day$; at a flow rate of 88,000 gallons per day ("initial winter average") nitrogen loading would be 0.5 g $N/m^2/day$. Under the septage-only plan assuming an average loading of 39,000 gal/day of effluent containing 75 mg/l nitrogen the nitrogen loading would be 0.55 g $N/m^2/day$.

We have conducted experiments where, for 13 years, we have added nitrogen to salt marshes at several rates (Valiela and Teal, 1974). Our levels of nitrogen addition have ranged from 0.1 $N/m^2/day$ to 1.1 g $N/m^2/day$, applied for a 6 month period during the summer. These levels of nitrogen stimulate the growth of grasses on our experimental plots. At the highest level of treatment we saw dramatic increases in biomass and some changes in species composition. Consumption of the plants by animals also increased. From these experiments and studies done elsewhere (Chalmers, 1982; Sullivan and Daiber 1974; Broome et al., 1975), the addition of 0.5 to 1.0 g $N/m^2/d$ should cause noticable changes in the vegetation of Hurley's Bog. The production of plants should increase as well as the species present, and to an extent the amount of change will increase with increased nitrogen loading. We anticipate there will be some removal of nitrogen in the bog, before the effluent enters Namskaket Marsh, and because the marsh is much larger than the bog we doubt that any pronounced changes in the marsh from nitrogen loading will be evident.

As mentioned above, freshwater swamps with standing water have been used for this purpose throughout the world; our research on salt marshes on Cape Cod has shown their potential to transform nutrients in sewage into productivity. This process can enhance coastal productivity, eventually serving as food for young fishes or shellfish. The possibility of combined use of fresh and salt brackish marshes also would greatly increase the treatment capacity of the wetland system---this may be important if Hurley's Bog is inadequate for treating the peak effluent volume.

C. Other Impacts

Problems in sewage disposal can arise from certain pollutants, such as petrochemicals and chlorinated petrochemicals (insecticides, PCB, etc.) as well as metals, such as lead, zinc, and cadmium. Because of the primarily domestic and commercial nature of the potential users of a septage or septage-sewage plant here, we do not feel this should pose special problems at Namskaket Marsh. Pathogenic bacteria and coliform bacteria are generally removed effectively by sewage treatment plants, although there is evidence that viruses may not be. Based on the literature on virus removal by rapid infiltration (EPA, 1980; Gerber, 1983) the reduction of pathogens occurs at several stages of the sewage treatment process.

Wastewater contains about 10^5 pathogens/l. Removal by secondary treatment can eliminate 90-99% of them and disinfection by chlorine or ozone can remove 25-99% of those remaining. This represents a tremendous removal rate but it is still possible for significant numbers of bacteria and viruses to remain in the effluent. When the effluent is applied to rapid infiltration beds there is a further reduction in pathogens. Bacteria and viruses are removed by adsorption onto soil particles. They are also killed or inactivated by drying and exposure to ultraviolet light, and grazed upon by certain animals such as worms. Under optimum conditions all the pathogens may be removed within a few centimeters of the surface of a rapid infiltration bed. It is known that bacteria are removed more efficiently than viruses, although both have been isolated from rapid infiltration sites many meters away. In those sites where viruses have been isolated, the effluent being applied was not a secondarily treated and had not undergone disinfection. Viral research in wastewater is a relatively new area of research since it is only recently that good techniques for isolating viruses have been developed. The treatment scheme proposed for Orleans involves considerably more treatment than wastewater often receives before direct disposal into estuaries, in many parts of the country. The potential for contamination of Namskaket marsh by pathogens from the treatment scheme seems exceedingly low if the hydrologic analysis is correct.

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ACKNOWLEDGEMENTS

This manuscript was prepared by Elaine Lynch, Margaret Harvey and Pamela Barrows. Figures were drafted by Nancy Murphy, Chuck Steacy, Jack Cook and Fritz Heide, of our Graphic Services section. Field assistance was provided by Richard van Etten, Karen Hickey, Robert Cooper and Adam Richman. Many residents and businesses in Orleans and Eastham provided information or logistical assistance with fieldwork, for which we are grateful.

This project was funded by the Town of Orleans, Massachusetts. Partial support came from the Department of Commerce, NOAA, National Sea Grant College Program under Grant No. NA80AA-D-00077(R/M-9).

APPENDICES

Appendix I Geographic and Hypsometric Statistics for Town Cove, Orleans Quadrangle, Massachusetts.

Depth (m)	Projected Area (m^2) a/	Depth Interval	Volume m^3	Including Channel
0.0	1.4×10^6	0.0-0.5	0.73×10^6	0.78×10^6
0.5	(1.3) " b/	0.5-1.0	0.49 "	0.54 "
1.0	0.68 "	1.0-1.5	0.32 "	0.38 "
1.5	0.60 "	1.5-2.0	0.29 "	0.34 "
2.0	0.55 "	2.0-2.5	0.27 "	
2.5	0.52 "	2.5-3.0	0.24 "	
3.0	0.45 "	3.0-3.5	0.21 "	
3.5	0.38 "	3.5-4.0	0.17 "	
4.0	0.29 "	4.0-4.5	0.12 "	
4.5	0.18 "	4.5-5.0	0.061 "	
5.0	0.071 "	5.0-5.5	0.019 "	
5.5	0.014 "	5.5-6.0	0.002 "	
6.0	0.0 (assumed)			

Entrance Channel in Town Cove:
Projected Area: 0.114×10^6 m^2
Volume: 0.228×10^6 m^2 (assume uniform 2 m depth)

Volume of Town Cove: 3.13×10^6 m^3.

Average Depth (A/V): 2.2 m.

Projected recharge areas (square meters)	
Total Town Cove and the outer Nauset embayment:	27.6×10^6
Outer Nauset embayment:	18.1×10^6
Terrestrial:	10.3×10^6
Estuary (including marsh):	7.9×10^6
Town Cove:	9.4×10^6
Terrestrial:	7.9×10^6
Estuary:	1.4×10^6

Perimeter of Town Cove: 6,200 meters

a/ Relative areas determined from bathymetric chart of Aubrey (this report), using USGS (1974) topographic map for the Orleans Quadrangle for surface areas.

b/ Value estimated.

Appendix II - Calculation of fluxes from porewater gradients

The flux of material from the sediment to the water column can be calculated using porewater gradients. The methods, assumptions and limitations of this approach have been widely discussed and are summarized by Berner (1980).

The expression used for calculating flux is:

$$J_i = C_o J_s / p_s (X/1- X) - {}_o D_s$$

where:

J_i = flux of dissolved constituent i between sediment and overlying water

J_s = flux of solid particles by deposition

C_o = concentration at the sediment water interface

p_s = density of sedimenting particles

X = porosity at depth X below which porosity is constant

$_o$ = porosity at sediment water interface

D_s = diffusion coefficient in the sediment of the ion of interest.

= concentration gradient at the sediment water interface.

The first term of the equation is to calculate the flux due to compaction. Since the sediment is being buried faster than the water there is a net flow of water upward. In Town Cove sediments where

C_o= max value of 20 x 10^6

J_s = .566 g cm^{-2} y^{-1}

p_s= approximately 1.3 g/cm^3

X = .6

Therefore the flux due to burial is equal to less than 1 uM M^2 y^{-1} and can be neglected. Only the second term needs to be considered.

$_o$ = varied in the cores and was measured (Table)

D_s = D_o/ F'

where D_o is the diffusion coefficient in free solution and F' is the formation factor.

D_o for NH_4^+ =(19.8 .4(T-25)x10^{-6} cm^2 s^{-1} Krom and Berner 1980b

F' = was approximated by using $^{-2}$ and neglecting the temperature dependent differences in viscosity between sea water and distilled water.

APPENDIX III Tidal Harmonic Constants for Goose Hummock Station

Table A III-1 lists the tidal harmonic constants derived from a computer analysis of 29 days of tide gage data from Goose Hummock, Orleans, Ma, starting on 22 July 1982. The method used was based on that of Boon and Kiley (1978), modified by us to provide the specific information of interest. The columns indicated in the table represent:

- NOS NO.: Constituent reference number assigned by the National Ocean Survey.
- CONST.: Abbreviation for each tidal constituent.
- SPEED: Number of degrees per hour that a particular constituent travels. A large number indicates a diurnal or faster tide; small numbers indicate longer period tide constituents.
- H: The amplitude of each harmonic constituent, which is one half of the range of each. Units are meters. These numbers have been corrected for the nodal factors for the particular location and period of time.
- KAPPA: Constituent phase relative to a local epoch.
- KPRIME: Constituent phase relative to Greenwich phase.
- ZETA: Tidal phase of constituent referred to the beginning of the time of record.
- °/o TSS: Percent of total sum of squares accounted for by each tidal constituent, a measure of the importance of each constituent at a specific location.

For a more complete description of the methods and terms discussed here, refer to Schureman (1971).

Estimates for the mean tidal range at this location over a month's period can be made from the value of the total sum of squares. If we let TR be the mean tidal range over the month's period, we can calculate this quantity by the following calculations.

SStotal = total sum of squares in series
SStide = total sum of squares accounted for by tidal motions
= SStotal x °/o TSS (total percent sum of squares).

The tidal range is:

$TR=2 \quad 2(SStide)/n$

where n is the number of observations (697 in our case).

For Goose Hummock, this calculation yields:

$SStotal=120.9\ m^2$

$SStide =0.9439 \times 120.9 = 114.1\ m^2$

$TR = 2 \quad 2(114.1)/697 = 1.14$ m Mean Tide Range = 3.75ft.

During Spring tides the total range will be greater, while during Neap Tides the tidal range will be less.

APPENDIX III (Cont.)

Tidal Harmonic Constants for Goose Hummock Station.

HAMELS-HARMONIC ANALYSIS METHOD OF LEAST SQUARES

STATION GH 41.80 69.99 75W YEAR 1982
29 DAY SERIES STARTING 7 22 9.6 HRS 697 OBSERVATIONS

NOS NO.	CONST.	SPEED	H	KAPPA	KPRIME	ZETA	0/0 TSS
1	M2	28.9841	0.521	156.87	151.9	115.48	79.33
2	S2	30.0000	0.064	207.23	197.2	119.21	1.17
3	N2	28.4397	0.115	105.28	103.1	112.87	3.87
4	K1	15.0411	0.083	255.26	250.0	189.91	2.71
5	M4	57.9682	0.116	251.15	241.3	168.38	4.01
6	O1	13.9430	0.094	241.97	242.2	261.80	2.46
7	M6	86.9523	0.017	358.11	343.3	233.96	0.09
9	S4	60.0000	0.002	252.33	232.3	76.29	0.00
12	S6	90.0000	0.001	281.55	251.5	17.49	0.00
36	M8	115.9364	0.005	156.32	136.6	350.78	0.01
11	NU2	28.5126	0.020	133.50	130.9	87.68	0.11
13	MU2	27.9682	0.013	106.51	106.6	-250.34	0.05
14	2N2	27.8954	0.014	102.88	103.4	-200.55	0.05
15	OO1	16.1391	0.004	268.56	257.9	-53.71	0.00
16	LAM2	29.4556	0.004	180.24	172.9	-36.71	0.00
18	M1	14.4967	0.007	248.62	246.1	-118.15	0.01
19	J1	15.5854	0.007	261.86	253.9	151.67	0.02
25	RHO1	13.4715	0.004	236.26	238.9	-108.34	0.00
26	Q1	13.3987	0.018	235.37	238.4	-55.82	0.09
27	T2	29.9589	0.004	205.21	195.4	-45.21	0.00
28	R2	30.0411	0.001	209.24	199.0	103.63	0.00
29	2Q1	12.8543	0.002	228.78	234.5	-13.44	0.00
30	P1	14.9589	0.023	254.27	249.5	240.49	0.22
33	L2	29.5285	0.015	183.86	176.2	-83.79	0.10
35	K2	30.0821	0.017	211.31	200.9	-99.48	0.08

SERIES MSL 0.66 SLOPE -0.000093 94.39
TOTAL SUM OF SQUARES IS 120.930260

APPENDIX IV. Equations used in Town Cove computer model.

TWO-DIMENSIONAL EQUATIONS:

The two-dimensional depth-averaged equations are presented below with non-linear terms analogous to the one-dimensional case underlined (e.g., Dronkers, 1964).

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x} \underbrace{(h+\zeta)\,\bar{u}}_{\mathrm{I}} + \frac{\partial}{\partial y} \underbrace{(h+\zeta)\,\bar{v}}_{\mathrm{I}} = 0 \qquad \text{Continuity}$$

$$\frac{\partial \bar{u}}{\partial t} + \underbrace{\frac{\bar{u}\partial \bar{u}}{\partial x} + \frac{\bar{v}\partial \bar{u}}{\partial y}}_{\mathrm{II}} = \frac{-g\partial \zeta}{\partial x} - \underbrace{\frac{C_D\, q\, \bar{u}}{(h+\zeta)}}_{\mathrm{III}} \qquad \text{X - Momentum}$$

$$\frac{\partial \bar{v}}{\partial t} + \underbrace{\frac{\bar{u}\partial \bar{v}}{\partial x} + \frac{v\partial \bar{v}}{\partial y}}_{\mathrm{II}} = \frac{-g\partial \zeta}{\partial y} - \underbrace{\frac{C_D\, q\, \bar{v}}{(h+\zeta)}}_{\mathrm{III}} \qquad \text{y - Momentum}$$

where

$$\bar{u} = \frac{1}{(h+\zeta)} \int_{-h}^{\zeta} u\,dz$$

$$\bar{V} = \frac{1}{(h+\zeta)} \int_{-h}^{\zeta} v\,dz$$

h = undisturbed water depth

ζ = tidal elevation perturbation

$q = (\bar{u}^2 + \bar{v}^2)^{1/2}$

C_D = drag coefficient

The underlined non-linear terms can be described as follows:

I) divergence of volume flux associated with region between undisturbed water depth and tidal free surface elevation.

II) advection of momentum

III) quadratic friction.

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APPENDIX IV (Cont.) Equations used in Town Cove computer model.

The momentum equations neglect Coriolis terms (linear) and horizontal diffusion of momentum (generally taken as linear).

RESIDUAL CURRENTS--DEFINITIONS

This section defines residual currents which result from a time-average of non-linear terms in the equations of motion. Consider the instantaneous depth-integrated flux in a rectangular channel:

$$q = (h+\zeta)\overline{u} \qquad (1)$$

where

$$\overline{u} = \frac{1}{(h+\zeta)} \int_{-h}^{\zeta} u(z)dz$$

We may consider the depth-mean flow as consisting of a time-averaged and periodic component

$$\overline{u} = u_E + u_p$$

$$u_E = \frac{1}{T} \int_{0}^{T} \overline{u}dt \qquad T = \text{tidal cycle}$$

u_p = periodic mean velocity component

similarly with ζ,

$$\zeta = \zeta_E + \zeta_p$$

$$\zeta_E = \frac{1}{T} \int_{0}^{T} \zeta dt$$

We take a time average of (1) over a tidal cycle:

$$\langle q \rangle = h \cdot u_E + \langle \zeta_p \cdot u_p \rangle$$

Dividing by h yields the Lagrangian mean velocity,

$$\frac{\langle q \rangle}{h} = u_E + \frac{\langle u_p \, \zeta p \rangle}{h}$$

APPENDIX IV (Cont.) Equations used in Town Cove computer model.

We find that the Lagrangian mean velocity consists of the Eulerian residual flow, u_E, and the stokes drift, $\frac{\langle \zeta_p u_p \rangle}{h}$, resulting from non-zero correlations between sea surface elevation and velocity. Defining $\frac{\langle q \rangle}{h} = u_L$ we may define a flushing time for a coastal channel of length L:

$$T_f = \frac{L}{u_L}$$